REBREATHER SAFETY

FMECA Volume 6: Top Down Faults

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Revision History

Revision	Date	Description
A	1st Aug 2004	Cases collated from earlier documents.
B0 – 11	2nd Aug 2006 – 14th Mar 2009	B0: Independent Review 2nd Aug 2006. Inclusion of section for Umbilical supplied Diving. B1: added item 7.13. B2: added Commercial dive tool hazards and O2 cells due to fatal accident due to diver not hearing alarm. B3: added submarine sonar hazard and ESD hazards. B4: added cold water faults. B5: Isolating ALV faults. B6 (4th April 2007): ALV fault added to fault 6.1. B7 (21st May 2008): Added ALV failure incidents and connector failures. Hypoxia monitor added. B8 (30th June 2008): OPV failures broken out as a separate section and detailed. Helmet oro-nasal valve failure added. Water drain faults added. B9 (28th Nov 2008): Diver thermal and respiratory shock added, commercial diver one way valves added, safety process fault section added. Deco risks added. B10 (28th Dec 2008): Cylinder risks separated. B11 (14th Mar 2009) Expansion of Sections 6.3 (Oxygen First Stage Overpressure hazards), p12 and Section 7.4 p24 (Make-up-gas First Stage Overpressure hazards) p23. Section 7.7 (Wrong Make-up-gas) expanded as a result of an accident study. Section 6.7 (Uncontrolled ascent) expanded. Numeration of requirements expanded so these can be audited using Mantis: Mantis uses the same enumeration.
B12 - 18	22nd May 2009 – 26th Aug 2010	B12: §6.10, §12.13, §12.14, §12.2, §12.3, §6.8, §10.10, §6.23, §18. Sections reorganised by their safety functions. B13 (28th May 2009): Review improvements. B14 (29th May 2009): Proofread and further review comments included. B15 (23rd Aug 2009): ALVBOV and Manual O2 injector FMECA top down merged into this document. Material safety excludes Delrin and POMs based on reports of lung burns from divers diving new rebreathers making extensive use of these materials. Fault §6.28 added, from a field failure. B17 (17th Dec 2009): Off-gassing material safety updated with PC.B18: Update to §6.7, §6.8, § 6.29, §7.9, §9.2, §0, §10.1, §10.13. Rev 18B (23rd Aug 2010): Added §6.29. Rev 18C (26th Aug 2010): Added §7.13, §7.14, §9.25, §17.17. §Rev 18C: §5.10, §5.11, §5.12, §5.13
C0-C5	To 20th Jan 2014	C0: Post PPE certification. Added O2 cell failure mode detail. C1: Updated Sections §6.10, §6.30, §13.5, §13.8, added Section §13.9. C2: Correction to §17.3, added §18.4 C3: More detailed consideration of respiratory collapses, IPO and cardiac events. C4: Added 8 corner check requirement §6.7, added detail to §11.1 and to §13.10. C5: Faults added from accident analysis
C6	1st Dec 2014	11.9 One-way valve faults separated and clarified. 14.3 Polarised or UV filtered mask risk added.

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1 PURPOSE AND SCOPE

This document is a top down Failure Mode Effect and Criticality Analysis of diving rebreathers, that is intended to catch all faults known in any rebreather, though with specific attention to the Open Revolution family of rebreathers developed by Deep Life Ltd.

By "Top down" it means this FMECA considers each functional requirement of the rebreather system in its fullest sense:

1. Gas Supply Containment Failures,
2. Provision of Oxygen,
3. Loop Volume Sufficiency,
4. Loop Volume Relief
5. Control and Information,
6. Oxygen Level Monitoring,
7. Carbon Dioxide Removal,
8. Flooding and Drowning
9. Other Rebreather Related Failures
10. Associated Equipment Failures
11. Decompression Computer Faults
12. Thermal Management Related Faults
13. Umbilical supplied Equipment specific
14. Diver Physiology Related Faults
15. General environmental hazards
16. Safety Process failures

This document serves a dual purpose, namely:

1. To provide a check list to ensure that top level failures are managed safely by the rebreather. This top down method is matched by a bottom up review of the electronics, mechanics, software/firmware and a hierarchical fault tree analysis down to component level.
2. To provide a structured framework for the analysis of equipment after an accident to determine whether or not the equipment contributed to, or caused, the accident The evidence can be compared with all possible causes to develop a "plausible cause" list, that can be further reduced using formal verification (mathematical modelling of the known dive profile to identify the point where the problem occurred).

All references to "the system" refer to the Open Revolution submission by Deep Life Ltd. References to "mandatory checks" refer to the pre-dive checks performed by that specific rebreather controller. However, the list of possible faults is that known on any rebreather.

This document covers the rebreather itself and essential diving equipment to use the rebreather. Separate equipment should have a separate FMECA or safety certification, and is included here only where the failure may cause a failure that may be associated with use of a rebreather.

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Every one of these requirements are listed under Mantis: the tool used by Deep Life to control specifications and verify in the design verification process that every requirement is met. Where there are many functional safety implications under one fault, these are enumerated to support unambiguous cross-referencing by Mantis.

2 SOURCE DATA

The failure modes listed in this document are drawn from numerous sources. The prime sources are listed in [1] to [7] in the references. Other sources include:

- HAZID and HAZOP studies,
- FMECA studies on contemporary equipment,
- Faults and incidents reported on rebreather internet forums,
- Coroner reports,
- Equipment failure reports issued by public health laboratories
- Warnings issued by rebreather manufacturers,
- Accident appraisal advice from accident investigators.
- Accident investigations.
- Faults found by Formal Modelling or verification.

Each fault mode attributable to equipment has been encoded in a formal fault model in the Open Revolution rebreather environment. This model is a Matlab model, which has been published by Deep Life Ltd to enable the safety of new rebreather designs to be verified.

The formal verification environment allows any of these faults to be selected, combined with any other(s), and then applied to verify the safety performance of the equipment under these fault conditions.

Efforts have been made to encourage other manufacturers to use, critique and extend these formal models. There has been some independent review of the models by others working on rebreather design. The objective is to create an industry-wide consensus on the formal fault models needed to verify the safe operation of rebreather apparatus.

3 STRUCTURE

This report classifies faults into groups, based on the section of the equipment associated with the failure.

There is an inevitable duplication of some failures. For example, counterlungs becoming detached is one failure, but it is also listed under WOB increase in the section on PPCO2 Control, as counterlung detachment is one cause of such an increase. The view was taken that it is better to include duplication than miss critical failure modes. This approach also simplifies the use of the fault list in HAZOP reviews.

No attempt is made to quantify the probability of the event occurring, as most risks can be removed or mitigated by design, and other depend too much on maintenance and use factors to make a quantitive risk probability assessment meaningful.

Similarly no attempt is made to differentiate between effects: in diving, almost all failures can result in death through drowning if the failure is not recognised and handled promptly. Failures tend to create or perpetuate a chain of events, spiralling down an incident pit until the diver is able to either arrest the sequence, or dies. This means that what may be small

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insignificant events can take on critical importance when least expected. The emphasis shall therefore be:

- For equipment design the emphasis need to be on elimination or mitigating risks, (i.e. prevention),
- For operations the emphasis need to be on equipment maintenance, awareness and monitoring,
- For training and dive practice the emphasis need to be on continuous checking and failure management.

4 SIL COMPLIANCE OBJECTIVE

The objective of this system is compliance with SIL 3 to 4 of EN 61508:2004 Parts 1 to 3 (Parts 4 to 7 are informative only). This requires a mean time between critical failure better than one billion hours, and a system availability of 100,000 hours subject to routine maintenance and preparation.

The SIL 3 to 4 objective has been concluded by applying the processes in Functional Safety with the ALARP principle (As Low As Reasonably Practicable risk), in the context of a rebreather which is supplied as an Open Circuit replacement with more than 10,000 units in use.

This top level fault list considers "plausible failures" as any failure with a probability greater than one in a billion hours of diving, multiplied by the number of faults listed, so the aggregate risk is less than 1 in 10^8 to 1 in 10^9.

It is recognised that diving is a hazardous activity and there is a base level of risk, which appears to be in the region of one fatal accident per 9,000 diver exposure years (for Open circuit diving)[1], which is one per 78 million hours in terms of elapsed time, but probably nearer to one in 100,000 hours of actual diving exposure. Application of Functional Safety principles would keep the contribution from equipment failure to less than 1 in 1000, giving a cumulative target for the equipment itself of 1 in 10^5 * 10^3, which is 1 in 10^8.

Rebreather use is associated with a higher accident rate. Analysis of these accidents using Functional Safety processes attribute a majority to equipment issues (specifically, rebreather issues). However, an order of magnitude increase in base risk is also observed which appears to be due to increased risk taking by sports rebreather divers (solo diving, extreme depths, cave diving, wreck penetration), compared to the Open Circuit diver, as well as likely more divers per annum carried out by the median rebreather diver compared to the median Open Circuit diver.[2] This work focuses on rebreather failures, but also includes fundamental risks of diving.

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1 P. Denoble, J. Caruso, G. de L. Dear, C. Pieper and R. D. Vann, "COMMON CAUSES OF OPEN-CIRCUIT RECREATIONAL DIVING FATALITIES", April 2008, accepted for publication in the Journal of Underwater and Hyperbaric Medicine.

2 A. Deas, V. Komarov, "Acceptable Risk Targets for Rebreather Diving", 2009, Paper in peer review for publication.

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5 GAS SUPPLY CONTAINMENT FAILURES

5.1 Cylinder explosion

Cause

Unsuitable cylinders, damaged cylinders or defective cylinders.

Poor filling technique.

Contamination.

Safety Implication

This results in catastrophic cylinder failure.

Prevention

Prevention is by using certified cylinders, with hydrostatic and visual tests as stipulated by a national authority, filled by trained gas technicians under clean conditions.

Functional Safety Implication

Explain safe gas handling in the user manual.

Use only certified cylinders.

5.2 Carbon Wrapped Cylinder Electrolysis

Cause

Electrolytic action between carbon and aluminium in the presence of sea water, due to lack of treatment of the aluminium before wrapping.

The sea water acts as a battery electrolyte, caused very rapid corrosion of the aluminium, and a delamination of the carbon wrap.

Safety Implication

This results in catastrophic cylinder failure.

Functional Safety Implication

Apply PVD Diamond-like Carbon or hard anodising or other suitable coating to aluminium before wrap.

Ensure users know not to use general carbon wrapped cylinders unless they have been properly assessed for marine use.

5.3 Plastic Core Decomposition

Cause

Plastic cored carbon wrapped cylinders are available.

Small rebreather cylinders are often filled too quickly, resulting in the gas in the cylinder reaching hundreds of degrees Celcius. The cylinder itself heats up more slowly due to its thermal mass, and its thermal losses to the environment. The hot gas causes thermal

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decomposition of the internal cylinder wall, if the core is plastic, which can run away if the filling gas is oxygen.

Use of valves with sintered filters are reported by BAM to cause failure of cylinders with plastic core, even with an air fill, due to heating effects.

Safety Implication

Cause need to be avoided, as it results in catastrophic cylinder failure.

Prevention

Do not use plastic cored cylinders for rebreathers, due to risk of them being used with oxygen, and general overheating risk.

Functional Safety Implication

User manual should describe the preventative action.

5.4 Carbon Wrapped Cylinder Core Delamination

Cause

Helium gas diffuses through the aluminium core because it is under stress, then collects at the interface with the carbon wrap, which is under less stress. The result is a bubble of helium, which spreads and delaminates the wrap from the core.

Safety Implication

This results in catastrophic cylinder failure.

Prevention

Inspect carbon wrapped cylinders annually.

Do not store helium in carbon wrapped cylinders for long periods.

Functional Safety Implication

User manual should describe the preventative action.

5.5 Oxygen fire from detritus in cylinder

See also Fault 6.10

Cause

Detritus from cylinder striking the valve seat in a high oxygen atmosphere.

Safety Implication

Oxygen fire, catastrophic failure of cylinder or valve.

Prevention

Prevent by design.

Functional Safety Implication

Fit a detritus tube to all rebreather cylinder valves.

Fit a sintered bronze filter to the detritus tube. Note ISO 10297 – 2006(e) requires a large filter surface area to prevent heating of the gas during filling processes.

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Considered further herein under oxygen fire risks.

5.6 Cylinder Valve Failure

Cause

Failure of valve (from wear, impact, oxygen shock, heat, thread). Detachment of seat.

Symptoms

Surface

Unwanted opening results in a loss of gas and a loud noise.

Dive

Loss of gas.

Recovery action during Dive

Abort dive.

Preventative action

Valves should comply to ISO 10297-2006(e).

Functional Safety Implication

Valves should comply to ISO 10297-2006(e).

5.7 Cylinder Valve O-ring or Regulator O-Ring Failure

Cause

Damaged O-ring, damaged thread, poor handling, O-ring wrong size, O-ring contaminated.

Symptoms

Surface

A loss of gas.

Dive

Loss of gas.

Recovery action during Dive

Abort dive.

Preventative action

Handle O-rings carefully and check for damage.

Functional Safety Implication

O-ring should be EPDM or an oxygen compatible material.

User manual should give guidance to user on handling O-rings and threads.

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5.8 High Pressure Burst Disk Related Hazards

Cause

Failure of burst disk to open or no burst disk.

Unwanted opening of the burst disk.

Symptoms

Surface

Failure to open does not seem to be a hazard other than as listed below.

Unwanted opening results in a loss of gas and a loud noise.

Dive

Loss of gas.

Recovery action during Dive

Abort dive.

Preventative action

Unless required by regulation, burst disks and over-pressure valves should not be fitted to dive cylinders: their safety function is to prevent an over-pressure. This can occur only because of:

- Over-filling. Dive filling stations should have a working over-pressure cut-off.
- Over-Heating. Dive cylinders have a burst pressure over twice the working pressure. This means the dangerous over-pressure is reached only in a fire with a full tank. It will be apparent to all that such a fire has occurred, and the tank can be handled once the fire has been extinguished and all tanks have cooled down. A cylinder that has been in a fire is condemned.
- Internal Fire. A fire inside a cylinder will generally result in the destruction of the cylinder.

The risk of unwanted burst disks opening, far outweighs the above risks. Burst disks fail not infrequently during dives. Some of the contributors have suffered burst disk failures on trimix dives when deep.

Functional Safety Implication

Do not fit burst disks to high pressure dive cylinders unless required by national regulations.

5.9 Intermediate Pressure Relief Device Related Hazards

Cause

First stage regulator seat leaks, is relieved by pressure relief device if there is no second stage demand valve.

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First stage regulator is of a pressure compensated type, and diver ascends if there is no second stage demand valve then the pressure relief disk may be needed.

Symptoms

Surface

If the relief device bleeds any significant amount of gas, then it produces a very loud noise.

Dive

Failure to open or not fitted: First Stage failure, can be catastrophic in a piston design, or diaphragm fails in a diaphragm design causes a loss of that gas source.

Accidental opening: Loss of gas.

Recovery action during Dive

Abort dive. Bail-out.

Preventative action

Fit an over-pressure relief device to all intermediate pressure systems if there is no automatic over-pressure relief device (such as a second stage demand regulator).

Functional Safety Implication

There are four failure modes that need to be considered:

1. Thermal rise in the temperature of an intermediate pressure line. The line volume is under 100cc (including regulators, line of up to 6mm internal bore and 1m maximum length). A bleed rate of 100cc per minute is sufficient even in a fire situation.
2. Over-pressure from a compensated valve, with reduction in ambient pressure. In the worst case of an uncontrolled ascent from 100msw to the surface, in 1 minute, a line containing 100cc at 10 bar relative intermediate pressure, will be over-pressurised by 10 bar. This is not a significant over-pressure and all components should withstand this easily. However for correct operation, the 10 bar should be relieved. This can be achieved within a few minutes by a 0.5 to 1 litre per minute flow.
3. Over-pressure from first stage regulator valve seat leakage or creep. The primary requirement is to signal the diver that the first stage is faulty. The over-pressure relief device should therefore give off a loud noise when it relieves pressure. The amount of leakage that it is reasonable to relieve is 1 litre per minute: this is based on ten times the volume of gas that is normally in the line being relieved – so a 100cc volume relieving 1 litre of gas per minute.
4. It is recognised that a large obstruction to the valve seat will cause a very large gas pulse which will likely burst the first stage diaphragm. Large obstructions should be avoided by fitting

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sintered filters on the inlets of first stage regulators, and where there is a possibility of a negative pressure (reverse pressure) being applied, then an outlet filter should be fitted to the first stage regulator or the system it connects to: this is mostly an issue for commercial diving gas manifolds.

Overall, the pressure relief device should relieve at least 1 litre per minute with a 50% over-pressure.

The devices used on the Open Revolution rebreathers have a relief rate of 1 litre per second (60 times higher). This meets the above requirement. The high flow rate does not appear to be a hazard, as it would take several minutes for a cylinder to empty and a SCUBA diver would turn off the cylinder within about 10s: a SSUBA diver would simply use an alternative bailout source (2 bail out cylinders are fitted to the SSUBA system with one way valves so a loss of gas from one cylinder does not cause a drain on the other cylinder).

5.10 Valve Outlet Profile Specification Error in DIN 477 & EN 144

Cause

The square profile specified in EN 144-2:1998 and DIN 477:1963 allows the O-ring on the end of the regulator to be extruded into the square profile of the valve, when the ambient pressure if more than the line pressure. This is a design fault with the standard, because divers do dive with cylinders turned off: for example, a Tech diver with O2 for decompression may dive with that cylinder off until it is needed. Fault usually needs an ambient pressure > 10 bar to manifest itself.

Symptoms

Surface

Loss of cylinder contents.

Dive

Freeflow of valve to regulator interface, losing gas.

Recovery action during Dive

Use a bail out gas source.

Preventative action

Do not use square profile valves. The EN 144-3 M26 profile does not suffer this problem, nor do G5/8 valves cut with the same circular profile.

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Functional Safety Implication

Consider all SCUBA seals under the condition where the ambient pressure exceeds the line pressure.

5.11 SCUBA Regulator Hose O-ring Retention Fault

Cause

The O-ring on common SCUBA hoses is retained when the line pressure is the same or more than ambient pressure, but is dislocated otherwise because there is no groove or retainer for the O-ring. Fault usually needs an ambient pressure > 10 bar to manifest itself.

Symptoms

Surface

Freeflow from regulator end of the hose.

Dive

Freeflow from regulator end of the hose, losing gas.

Recovery action during Dive

Use a bail out gas source.

Preventative action

Use SCUBA hoses fitted with retained O-rings: these can be identified easily because they generally use a double O-ring.

Functional Safety Implication

Consider all SCUBA seals under the condition where the ambient pressure exceeds the line pressure.

Use a double O-ring, with each O-ring retained by a groove, for the regulator connection.

5.12 First Stage Regulator O-ring Retention Design Fault

Cause

O-rings on the seat assembly of some regulators are retained when the line pressure is the same or more than ambient pressure, but are extruded inwards otherwise because there is no groove or retainer for the O-ring. Fault usually needs an ambient pressure > 10 bar to manifest itself.

Symptoms

Surface

Freeflow from first stage regulator.

Dive

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Freeflow from first stasge regulator.

Recovery action during Dive

Use a bail out gas source.

Preventative action

Check all regulator assemblies to ensure O-rings are retained with positive and negative ambient pressures with respect to line pressure.

Functional Safety Implication

Use only those regulators that can retain all O-rings under positive and negative pressure, in applications where negative ambient to line pressures can occur: e.g. saturation diving, technical diving, decompression diving.

5.13 Hose sheath expands and bursts

Cause

The outer sheath of helium and oxygen hoses need to be vented to allow gas that migrates through the core to dissipate, otherwise offgasing will cause the hose to fail after long exposures to pressurized gas. See example below: gas is OFF and the end of the hose is open as the hose in the photograph expands!

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Symptoms

Surface

Gas hose sheath expands and bursts.

Dive

Ditto. Hose is still useable.

Recovery action during Dive

None required: hose is still useable.

Preventative action

All HP and LP gas hoses should have vented sheaths.

Functional Safety Implication

Use only vented sheath hose: these have perforations every centimetre, through the sheath, on four sides of the hose.

6 OXYGEN SETPOINT FAILURES

6.1 Oxygen Cylinder Empty

Cause & Prevention

Use of empty cylinder: will not pass pre-dive checks but user could dive anyway.

Diving with not enough O2 for the dive: system enforces dive abort when O2 consumption and O2 remaining do not allow user to reach surface with 50 bar in tank.

A leak. System enforces abort when insufficient O2.

Hose failure from O2. Forces bail-out and abort of dive.

First Stage Failure, including over-pressure relief, O2 ring failure. Forces bail-out, and abort of dive. Dive abort can be on Semi-Closed. This situation is the worst-case test case for Auto-ShutOff valve control.

Safety Implication

1. System manages each failure mode, and where not recoverable, forces Bail-out to open circuit or Make-Up-Gas flush-and-fly unit in semi-closed mode.
   Important that user is not allowed to dive unless there is enough O2 to reach the surface, including deco. System should monitor Make-Up-Gas and O2 levels. O2 fraction should not be allowed to drop below that of air at the same depth, and projection should use a 1.76l/min of O2 in calculating this availability, plus the loss of gas during ascent (using the known maximum dead volume of the loop).
2. Issue where hypoxic Make-Up-Gas is used is a serious one: diver should be warned.

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6.2 Oxygen Cylinder Switched Off

Cause

Switched off on dive boat after pre-dive checks, and forgetting to switch on again.

O2 cylinder accidentally turned off during dive, due to handle rubbing on something. Use of soft materials (elastomers) for the cyclinder valve knob makes this problem occur more often than using hard handles, as does some ribbing patterns on the handle.

Symptoms

Handled, in case of Low O2, by the Injector-led O2 controller finding an imbalance between injected gas and measured gas, then going into diagnostic mode, finding that injecting gas causes no gas, and treats failure first as a cylinder-valve-shut failure, then, if user confirms valve is open, as an injector failure. If second injector has same fault, requests user to turn on cylinder valve.

Recovery action during Dive

Urgent. Open O2 valve, ready to bail out to open circuit or Make-Up-Gas flush-and-fly unit in semi-closed mode. User is advised of this action, and system forces it with the Auto ShutOff valve.

Preventative action

This is a common fault, as the O2 valve knob sticks out from the cylinder and is easily rubbed. The worst position is when the O2 cylinder is hung like a stage, when the valve rubs on clothing.

Check position of valve and ensure it is covered, but still accessible.

Do not use soft materials for cylinder valve knobs.

Functional Safety Implication

1. System should not allow the oxygen cylinder to be switched off prior to the unit being switched on, unless the unit is already underwater when it is switched on, in which case the situation is handled as during the dive, as described below.
2. System should monitor O2 injector and O2 pressure. Where a mismatch occurs, the error message should be specifically “O2 Tank Valve is Closed. Open it!” Requires a digital contents gauge on the O2 and Make-Up-Gas tanks coupled to the CCR controller.
3. It is noted that OMS has have stopped supplying rubber knobs due to their greater risk of “grabbing” and turning themselves off or on. OMS have switched to hard plastic knobs with a surface that is less likely to move with friction.

6.3 Oxygen First Stage Failure

Same as cylinder contents empty, but sudden onset.

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This fault mode includes other causes, such as the 15 micron filter being blocked prior to the O2 injectors, blockage of all O2 injectors. All have the same effect.

6.4 Oxygen First Stage Over Pressure

Cause

- Wear of regulator.
- Partial oxygen fire of valve seat material.
- Poor maintenance of regulator.
- Corrosion, particularly of sintered filters causing breakup of the filter.
- Poor design of regulator.
- Icing of regulator.
- Structural failure of regulator
- Poor adjustment of regulator.
- Foreign material under valve seat from tank or from reverse flow into regulator.
- Wear of valve seat.
- Failure of valve seat.
- O-rings not retained with negative pressure.

Symptoms

Surface

In mCCRs and iCCRs with over pressure less than the intermediate hose rupture pressure, and below that at which an over-pressure release triggers, an over-pressure causes an excess oxygen flow. The magnitude of the possible excess flow can be severely limited: see Functional Safety implications.

In eCCRs using solenoids, the injector can seize. If a solenoid is used, very small deviations of intermediate pressure can result in the solenoid becoming stuck open or stuck shut: both are safety critical failures. At a higher pressure, an over-pressure valve should lift, and at higher pressures still the intermediate pressure hose can burst or creep out of its fitting.

In eCCRs using variable orifice valves, there can be a high tolerance of intermediate pressure variations, maintaining the operation of the PPO2 control system to pressures up to and above the hose.

With large increases in over-pressure that may not be limited by an over-pressure valve: in tests with over pressure gauges venting 600 lpm with just a 4 bar overpressure, the first stage diaphragm still ruptures violently, followed by a rapid release of the tank contents.

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In an eCCR if the batteries are low, that use a solenoid, the solenoid can fail to fire before low battery warning given. This may be observed as a failure to calibrate under some conditions, or it may fail to failure to hold a set point. The high or low O2 Alarm should sound.

When the over-pressure valve fires, it causes a loud noise, alerting the diver to the failure.

Dive

As per surface symptoms, except instead of failure to calibrate, a failure to hold set-point may be observed in solenoid eCCRs.

Recovery action during Dive

Urgent. Bail out to open circuit or Make-Up-Gas flush-and-fly unit in semi-closed mode.

Preventative action

1. Service First Stage regulators annually and check interstage pressure during servicing.
2. Inspect First Stages regularly for signs of corrosion or damage.
3. Fit an over-pressure valve to the First Stage regulators that trips within 4 bar of the normal operating pressure. Note that too narrow a margin can cause accidental trips when a diver makes a rapid ascent.
4. Fit a sintered bronze filter to the detritus tube in the valve or regulator, to prevent foreign material moving from the the cylinder to under the valve seat.
5. Fit and use fresh batteries in eCCRs.
6. Use as oxygen compatible valve seat material as possible within ALARP.

Functional Safety Implication

1. Apply all of the preventative actions listed above.
2. In mCCRs, it is possible to use an intermediate pressure hose that can withstand the full tank pressure: for example, a 3.8mm O.D., 0.8mm I.D. PVDF hose can withstand 300 bar. This hose limits the flow rate under over-pressure conditions. The over-pressure valve is not needed under these conditions, but need to be fitted for some compliance purposes.
3. In eCCRs, it is possible to either use a hose that withstands 300bar, such as Tungum tube or the PVDF hose, or a SCUBA hose with a burst pressure exceeding 120 bar (for one minute).
4. Some solenoids have only a narrow range of intermediate pressures they tolerate: solenoids and injectors should operate correctly from near 0 bar to at least 130 bar, to ensure the solenoid or injector does not fail before the hose.

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5. It is a requirement to verify the O2 injector works for all possible O2 intermediate pressures: from near zero to in excess of the burst pressure for the hose.
6. All O.R. implement meet all these requirements and implement all features listed as preventative: no N.C. solenoids are used (variable orifice is used).

6.5 Oxygen Hose Leaks

Cause

Wear, poor maintenance.

Symptoms

Surface

Failure to calibrate. Failure to hold set point during pre-breathe. Low O2 Alarm Sounding. Oxygen contents gauge showing low or audible air loss from cylinder.

Dive

Failure to hold set point. Low O2 Alarm sounding. Oxygen contents gauge may show empty. Bubbles in water.

Recovery action during Dive

Urgent. Bail out to open circuit or Make-Up-Gas flush-and-fly unit in semi-closed mode.

SSUBA rebreathers continue using Bail-Out-Gas.

Preventative action

Pre-dive checks.

Functional Safety Implication

Monitor O2 usage (requires O2 contents gauge and declaration of tank size). Give specific warning of leaking hose.

SSUBA should have sensor to detect umbilical gas pressure, or gas supply pressure (as each source has a different pressure, the supervisor can identify a drop in pressure).

6.6 Oxygen Solenoid or Injector Stuck Open

Cause

- Corrosion.
- Poor maintenance, allowing salt crystals or contaminates in unit.
- High Interstage pressure. Solenoid injectors may become unreliable at pressures above as little as 8.5 bar.
- Low Battery.

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- Oil contamination resulting in carbonized deposits in the solenoid or injector.
- Oxygen being exhausted at depth, rebreather then returns to the surface, sucking contamination into the injector or solenoid in the process.
- Failure of the spring in the solenoid valve or injector.

Symptoms

Surface

Failure to calibrate. Failure to hold set point during pre-breathe. High O2 Alarm Sounding. Counter lungs full.

Dive

Failure to hold set point. High O2 Alarm sounding. Excessive buoyancy. Can hear gas being injected at all times.

Recovery action during Dive

Urgent. Close O2 valve. Bail out, or Make-Up-Gas flush. Option to fly manually using O2 valve or to go semi-closed.

Preventative action

Regular service. Lube and ensure solenoid clean. Check mesh filter above solenoid. Recharge Batteries.

Functional Safety Implication

1. The oxygen injector should not be a solenoid, but a variable orifice valve, so that when it fails, the failure state maintains the average oxygen consumption.
2. Fit an Auto bailout and shutoff valve.
3. The gas supply should have a normally-open shut-off valve fitted, such that if the PPO2 is too high, then it shuts off the gas supply to the injector. That shut off valve may be a solenoid or another type of valve: the principle of diversity means that it should be a different type of valve than the main oxygen injector it is protecting.
4. Injectors and solenoid should be protected from contamination by both sintered and membrane type filters before and after the injector.

6.7 Oxygen Solenoid or Injector Stuck Closed

Cause

- Corrosion.
- Poor maintenance, salt crystals or contaminates in unit.
- Low battery.

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- High interstage pressure. Solenoid injectors may become unreliable at pressures above as little as 8.5 bar.
- The solenoid injector on one contemporary rebreather fails to operate when cold and the controller has a low battery.

Symptoms

Surface

Failure to calibrate. Failure to hold set point during pre-breathe. Low O2 Alarm Sounding.

Dive

Failure to hold set point. Low O2 Alarm sounding.

Recovery action during Dive

Urgent. Switch to SCR mode, then near surface to pure O2 mode.

Consider bail-out.

Preventative action

Regular service. Lube and ensure solenoid clean. Check mesh filter above solenoid. Fresh batteries.

Functional Safety Implication

1. The oxygen injector should not be a solenoid, but a variable orifice valve, so that when it fails, the failure state maintains the average oxygen consumption.
2. Fit an Auto bailout and shutoff valve.
3. Check the injector operates at all 8 corners of:
   a. Temperature, High and Low
   b. Battery, High and Low
   c. Intermediate Pressure, High and Low

   And ensure alarms are set to ensure equipment operates within those corners.

   4. Do not allow O2 setpoints below 0.7 atm, as they may otherwise be insufficient time for the diver to address this fault mode.

6.8 Oxygen Manual Injector Failure Open or Closed

Cause

Stuck on: corrosion, salt deposits in moving parts.

Stuck off: poor maintenance, internal damage, over-pressure.

Supply off: Failure to plug hose on properly, use of quick disconnects that are accidentally disconnected.

Either state: mechanical shock.

Symptoms

Surface

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Failure of pre dive checks.

Dive

Loss of gas from loop, flooding of loop.

Recovery action during Dive

Urgent. Reconnect Hose or re-screw injector down. Bail out if loop flooded.

Preventative action

Pre-Dive checks.

Functional Safety Implication

Eliminate the failure points: assess the manual O2 injector for corrosion, under pressure, over-pressure, opportunity for mechanical damage design out the manual O2 injector as a failure point.

Eliminate the oxygen manual injector unless the rebreather operates using manual injection as a primary PPO2 control method: on eCCRs the diver should inject make-up-gas, not oxygen.

6.9 Wrong Gas in Oxygen cylinder

Cause

Nitrox fill or gas other than 100% oxygen.

Symptoms

Surface

Failure to calibrate (maybe). Failure to hold set point. Lungs full.

Dive

Failure to hold set point (maybe). Excessive buoyancy and injector function.

Recovery action during Dive

Bail out (diver does not know what gas he is breathing).

Preventative action

ALWAYS analyse your gases after a fill.

Functional Safety Implication

Calibrate the O2 Cells in air (by detecting when the scrubber can is open). Make provision for saturation environments.

Check the O2 injector by a positive pressure test during startup, and check O2 Cell response is as expected.

6.10 Oxygen fire

Cause

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Poor O2 handling.

Organic contamination.

Poor maintenance.

Unsuitable materials.

Poor design.

Silicone oil filled pressure gauges, oil leaking (numerous O2 fires from this source)

Preventative action

Proper design and maintenance procedures.

Proper training of operators.

Use gases with 23% less 02.

Functional Safety Implication

Perform a full oxygen assessment of all materials, flows and components in contact with high or medium pressure oxygen in accord with the latest guidelines for oxygen component assessment published by NASA[3] and the American Society for Testing and Materials.[4]

Specific assessment shall be made with regard to risks of:

1. Particle impingement.
2. Mechanical Impact.
3. Pneumatic impact.
4. Flow Friction.
5. Galling and Frictional Heating.
6. Rapid pressurisation.
7. Resonance.
8. Electrical arcing.
9. Adiabatic compression.

The assessment shall be verified by oxygen surge testing to ISO 10297 – 2006(e) shall be carried out on all high pressure oxygen components, and broadly similar tests on medium pressure oxygen components.

- Viton O-rings are the only O-rings suitable for high pressure oxygen: these shall be 90 durometer or greater for high pressure gases, and 70 durometer for low pressure. Viton has poor performance when exposed to ozone (from welding), and has poor wear properties.
- All lubricants require an auto-ignition pressure to be tested in pure oxygen and that pressure should be at least 50% higher than their maximum service pressure. Fire and off-gassing will likely result otherwise.

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3 K. Rosales, M. Shoffstall, J. Stoltzfus, "NASA/TM-2007-213740 Guide for Oxygen Compatibility Assessments of Oxygen Components and Systems", NASA March 2007 available from http://ston.jsc.nasa.gov/collections/TRS/

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- The pressure gauges should not have an oil or silicone oil fill, to avoid the risk of the oil leaking into the hose or contaminating the hose.

6.11 Calibration using wrong gas

Cause

User error and design omission allowed user to dive with 60% O2 in cylinder used as 100% O2. Almost a fatality in both cases.

Preventative action

Calibrate using air when scrubber is open, then check during descent near surface.

Functional Safety Implication

1. Rebreather itself should check the O2 composition before every dive. It has calibrated O2 Cells (if the recommendation to force calibration in air is followed), and can inject O2 and check the composition of the loop gas on the surface to give an injector call. It is not complex to compensate the injector call for depth, so that no gas switch can introduce a low FO2 gas.
2. Auto Shut Off Valve would have prevented the problem affecting the diver's safety.
3. Voice annunciation of the resulting low PPO2 level would have prevented the problem affecting the diver's safety.

6.12 Solenoid Stuck Shut, due to rise in Intermediate Pressure

Cause

Rapid ascent in combination with O2 solenoid having narrow operating range.

Preventative action

1. Ideally, eliminate O2 solenoids: they have no place as a rebreather injector because both their failure modes are non-fail-safe.
2. If solenoids are used, ensure all failure modes are minimised and protected by suitable monitoring and shutoffs.

Functional Safety Implication

1. Carry out a full safety verification and assessment of the O2 injector to ensure it operates correctly with all possible intermediate pressures.
2. In any case, solenoids should operate with both compensated and non-compensated regulators, as divers frequently change regulators.

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6.13 O2 orifice motor driver failure (orifice type injectors)

Cause

Poor maintenance, or failure of component: motor, position sensor, etc.

Symptoms

Surface

PPO2 should not equal 0.7ATA.

Should be detected automatically, as PPO2 level changes but the output of the position sensor is constant.

Dive

Should be detected automatically, as PPO2 level changes but the output of the position sensor is constant.

Recovery action during Dive

None required if system recovery is sufficient. If second unit fails, then bail out.

Preventative action

Check motor operational range during self check sequence.

Functional Safety Implication

1. Should be detected automatically, as PPO2 level changes but the output of the position sensor is constant.
2. System should connect the second driver to the control loop and user is advised of this action.
3. Urgent (when PPO2 level increases beyond the set point after the connection of the second driver), user should be required to Flush or ascend.
4. Use direct orifice imaging to ensure orifice is not blocked or shifted.

6.14 Use of O2 instead of Make-Up-Gas

Cause

Diver injecting O2 instead of Make-Up-Gas

Preventative action

Eliminate manual O2 inject.

Functional Safety Implication

Eliminate manual O2 injection.

6.15 Use of hypoxic Make-Up-Gas when entering water

Cause

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Diver using a gas with a FO2 of less than 16% for dives to less than 80msw, breathing from that gas near the surface.

Preventative action

Proper training and instruction in manual to use a FO2 in the Make-Up-Gas of 16% or more.

Functional Safety Implication

Detect what the Make-Up-Gas gases are and run as a pure O2 rebreather automatically when above 6m.

6.16 Use of hypoxic Make-Up-Gas in ascent to surface

Cause

Loss of O2.

Use of wrong bail-out gas.

Use of wrong cylinder of gas.

Poor training.

Preventative action

Monitor O2 and Make-Up-Gas gases.

Functional Safety Implication

Eliminate manual gas injection.

Ensure O2 injector can keep breathing loop at full pressure at maximum rate of ascent (120m/min). Include torpedo test and fast ascent test in O2 injector verification.

6.17 Uncontrolled ascent (max 120m/min) with low PPO2

Cause

Loss of weight belt.

Catastrophic failure of buoyancy control device or injector.

Suit injector stuck on.

BCD injector stuck on.

User pressing the wrong button on the BCD inflator.

Entanglement with a towed object.

Entanglement with an SMB or lift bag.

Preventative action

Improved training to handle SMBs and Lift Bags properly.

Keep weight belts to simple belts rather than weight jackets.

OPV should be fitted to inhale counterlung to ensure gas flow from injectors does get to the inhale counterlung.

Functional Safety Implication

1. Covered by “end to end” clause.
2. Ensure PPO2 can be maintained with 120m/min ascent rates by specific inclusion in O2 injector verification plan.

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3. To avoid this fault, the rebreather should not allow PPO2 set points which are lower than the corresponding fraction of O2 in air, until it becomes necessary to limit CNS exposure. Use of PPO2 not less than air, to at least 30m, is recommended.
4. Note OPV should be fitted to inhale counterlung, not exhale counterlung. If the OPV is fitted to any point between the diver's exhale flapper valve and the inhale counterlung, a reverse gas flow occurs on very fast ascents, during which all injected oxygen is swept out of the rebreather as the flow moves from the inhale counterlung towards the OPV. This is recorded as a separate fault mode to ensure it is not missed.
5. Suit and BCD supplies should be quick release.

6.18 PPO2 low due to injection not keeping up with demand

Cause

User error and design limitation.
User flushes loop with hypoxic Make-Up-Gas.
Overlap with some other errors, such as running out of O2 or injector failure.

Symptoms

Dive

Counterlungs empty.

Recovery action during Dive

Control software should check the rate of the depth sensor and PPO2 cells and reject slow sensors.

Preventative action

User is advised to decrease the ascending rate. Service regularly and test /inspect.

Functional Safety Implication

1. Eliminate design limitation: injector should be able to provide at least 12l/min of O2.
2. Manual flush rate should be limited so that with no O2 in Make-Up-Gas gas, user cannot reduce the PPO2 to below 0.2.

6.19 Low PPO2 set point followed by rapid ascent.

Cause

User error and design limitation. Implicated in several fatalities where user has a PPO2 set point of 0.4, then ascends rapidly. This is a special hazard near the surface where the diver does not have time to respond to a failure.

Recovery action during Dive

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Control software should check the rate of the depth sensor and PPO2 cells and reject slow sensors.

Preventative action

The min PPO2 set point, when shallow, should allow the diver to "pop" to the surface without the PPO2 falling below 0.21.

Functional Safety Implication

1. The rebreather should increase PPO2 to operate as a pure O2 rebreather above 6m.
2. The injector should be able to inject 12l/min.

6.20 ALV freeflow with hypoxic Make-Up-Gas near surface

Cause

ALV leakage or freeflow on entering the water, with hypoxic Make-Up-Gas, resulting in diver hypoxia.

Manual flush, where Make-Up-Gas is hypoxic.

Preventative action

Not to start dive unless PPO2 is 0.7, not to allow hypoxic Make-Up-Gas on surface unless injectors can achieve at least 12l/min of O2.

Functional Safety Implication

1. Hypoxic Make-Up-Gass should be run via a manifold and not used near the surface.
2. Detect what the Make-Up-Gas gases are and decline the dive if hypoxic on surface.
3. PPO2 should be 0.7 or above to start dive.
4. O2 injectors should be able to achieve 12l/min.
5. ALV injection rate should be limited to 12l/min.

6.21 ALV freeflow with high PPO2 at depth

Cause

ALV leakage or freeflow at depth with Make-Up-Gas having excessive FO2. See also fault 7.1.

Manual flush at depth with Make-Up-Gas having excessive FO2

Switching the wrong gas on a manifold.

Preventative action

Dive training to use appropriate gases for Make-Up-Gas.

Functional Safety Implication

1. Hyperoxic Make-Up-Gass should be run via a manifold and switched out at depth, such as by turning the cylinder off and manifold off.
2. O2 injectors should be able to achieve 12l/min.

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6.22 Left to Right Flow, instead of safer Right to Left loop flow

Cause

Rebreather uses left to right flow, so oxygen addition is on right counterlung if diver keeps to convention of "Rich on Right". When a problem occurs, this means Make-Up-Gas is added to gas being inhaled instead of oxygen (because oxygen has to pass right around the loop as it si plumbed into the exhale counterlung). This can be hazardous if Make-Up-Gas is hypoxic.

Right to left flow follows a maritime convention for colours (Port and Starboard lighting), so boat skippers or dive masters can identify easily the direction a diver is heading (assuming breathing hoses are marked).

Preventative action

1. Use Right to Left loop flow, with Rich O2 on right, Make-Up-Gas on left.
2. Red on left, green on right also keeps with the maritime convention of
3. the use of colours to designate port and starboard, which may be a
4. slight safety benefit in recognising divers heading towards or away
5. from a vessel under some circumstances.

Functional Safety Implication

Covered by end-to-end scope: use right to left flow.

6.23 Hypoxia when OPV is on exhale counterlung during fast ascent

Cause

Under conditions of fast ascent, the expansion of the gas in the inhale counterlung can exceed the breathing rate of the diver. Under these circumstances, if the rebreather's OPV is on the exhale counterlung then the gas leaving the inhale counterlung flows both through the mouthpiece one way valves into the exhale counterlung. During the diver's exhale, all the gas expanding from the inhale counterlung flows back through the scrubber. In flowing back through the scrubber, the gas carries with it the oxygen that is injected between the two counterlungs in most rebreather designs. The result is that the majority of the injected oxygen does not flow to the inhale counterlung, but out to the exhale counterlung, where it is vented. This results in the PPO2 in the breathing loop plummeting.

This fault was found during verification of a rebreather using Functional Safety procedures, but since then, may be implicated in one or more fatal accidents.

Preventative action

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The OPV shall not be fitted to any position in the breathing loop that is between the inhale counterlung and the mouthpiece exhale one-way valve.

Functional Safety Implication

Basic safety requirement: the OPV shall be fitted only to the inhale counterlung or inhale hose (between inhale counterlung and mouthpiece). It shall NOT be fitted to any position in the breathing loop that is between the mouthpiece exhale one-way valve and the input to the inhale counterlung (following the direction of the normal gas flow).

6.24 SCR has insufficient oxygen in gas

Cause

Poor training, or lack of training.

SCR has insufficient oxygen in the gas to support the diver's metabolism and ascent rate.

Preventative action

1. Ensure gas mix is correct. If not, the diver should shut it off and use an alternative gas source.
2. Monitor PPO2
3. Mark SCR oxygen cylinders clearly stating that use of gases with an oxygen content less than X, will result in hypoxia and death.

Functional Safety Implication

Monitor the PPO2, and provide automatic bail out if the PPO2 cannot be maintained on the mixture.

A SSUBA rebreather will not switch over to bail-out automatically, so the diver shall either switch off the umbilical supply so the bail-out gas is used, or bail-out. Due to the delay in switch over to a bail-out gas, it is safer for the SSUBA diver to go to freeflow or open circuit.

6.25 Passive oxygen addition rate incorrect (mCCRs, PA-SCR)

Cause

Design fault with the oxygen dosing valve.

Damage to the oxygen dosing valve.

Use of incorrect Intermediate Pressure.

Valve blockage.

Mechanical damage.

Salt water ingress, drying and salt deposition.

Damage to the valve through particle impingement, adiabatic compression.

Thermal expansion or contraction outside the design limits.

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Preventative action

Check the flow rates of dosing valves in both passive and active addition modes before every dive.

Functional Safety Implication

1. Assess all oxygen dosing valves stringently.
2. Where electronic means to do so exists, measure the flow rate of all oxygen add valves before each dive and during the dive.
3. Follow up on all reports of any oxygen dosing valve failure to ensure all risks are mitigated to the extent possible.
4. Emphasise in training and in manuals the need to monitor PPO2 throughout the dive.
5. Emphasise in training and in manuals that if the counterlungs fill unexpectedly, to bail out immediately, and assess the safety of the loop before going back onto the loop, following good procedures when doing so.
6. Where within ALARP, provide a sound when the dosing button is depressed so diver knows that gas is being injected. This can be achieved using a reed across the port that introduces the gas to the rebreather. A white noise or pink noise is much more acceptable to divers than a tone.
7. Provide strong tactile feedback on the dosing button that is present only when gas is connected.

6.26 Oxygen addition button seized or stuck

Cause

Corrosion.

Silt behind the button preventing it being depressed.

Salt crystalisation around or in the button mechanism.

Foreign material entrapped in mechanism.

Hydraulic lock.

Spring action insufficient to overcome friction.

Spring develops a set after a long period of compression.

Preventative action

Button should be plastic and metals should be of a type that does not corrode.

Diver should be trained to wash equipment thoroughly after each dive.

Functional Safety Implication

Assess all buttons in silt saturated conditions, with worst case salt crystalisation, and for foreign material.

Provide silt washout ports on buttons.

Provide ports for water to escape from button.

Assess gas addition buttons for both fully lubricated and dry conditions.

Larger than normal safety margin should be used for the springs in injectors.

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User manual should instruct user to check for injector faults in use.

6.27 Inaccessibility of oxygen addition button (mCCR, iCCR)

Cause

Poor routing of the gas feed to the button.

Failure to provide a means to fix the button.

Failure to enable the gas hose to the button to be traced.

Locating the button in a region that is cluttered, e.g. shoulders.

Partial incapacity of the diver, from dry suit or equipment restrictions on diver movement.

Preventative action

Oxygen addition.

Functional Safety Implication

1. Assess button location with the widest spectrum of diver sizes.

2. Ideal location appears to be just above the crotch: all divers can find it, and have mobility of their hands just above that region.

3. Provision shall be made to properly attach the dosing device, such as belt loops.

6.28 Oxygen Sensor Temperature Compensation Error

Cause

Failure of sensor temperature compensation. This can result in errors in oxygen readings of 50% or more.

Temperature compensation circuits are generally not matched to the sensors. The sensor has a long thermal time constant (typically 30 minutes), but the compensation thermistors have a fast time constant. If these are not matched digitally, then oxygen calibration may be performed using a sensor that is at a very different temperature to the thermistor, resulting in errors of 20% or more but most importantly, **it usually affects all the sensors in the same way that are calibrated at the same time.**

Preventative action

Equalise the time constant of the thermal compensation thermistor and the oxygen sensor: this is not achieved simply by mounting the thermistor on a board with the sensor.

Functional Safety Implication

1. Check effect of calibration by inserting sensors stored in a refrigerator, calibrating, then performing a 0 to 2.3 bar PPO2 linearity check.
2. Apply digital temperature compensation, ensuring that thermistors are not shared between oxygen sensors (as it introduces a common mode failure otherwise).

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6.29 PPO2 Error due to Helium Ingress to Pressure Sensor

Cause

Use of a rebreather in a helium environment results in helium ingress to the reference chamber of the pressure sensors, and this produces an offset. If oxygen sensors are then calibrated using the ambient pressure data, the error can be considerable.

This error usually affects all the sensors in the same way that are calibrated at the same time.

Preventative action

Check the pressure reading is actually ambient pressure.

Functional Safety Implication

1. During the calibration process, request the user to confirm the ambient pressure.
2. Limit the ambient pressure reading to that which actually represents surface atmospheric pressures in diving: 700mbar to 1086mbar.
3. Redundant pressure sensors to estimate the magnitude of the drift.

6.30 Depth Exceeded for Absolute Pressure Regulators

Cause

The diver dives deeper than the constant flow depth limit, determined by the intermediate pressure supplying a constant mass flow injector**. Only occurs with rebreathers that use an absolute pressure regulator.**

Preventative action

Check the pressure reading is 2.5 bar above the maximum ambient pressure that may occur during the dive.

Functional Safety Implication

1. Emphasise the intermediate pressure limits in the user manual.
2. Use a high intermediate pressure as factory standard, so if the diver has a low pressure then it will be detected during pre-dive checks, where the flow rate is checked.

7 LOOP VOLUME SUFFICIENCY FAILURES

These are failures to maintain sufficient loop volume for the diver to breathe.

7.1 Make-Up-Gas Cylinder Empty or Umbilical Supply Lost

Cause

Someone forgot to fill the cylinder, or a bad leak from any part of the cylinder to ALV routing.

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ALV freeflow due to poorly designed or adjusted ALV or hydrostatic pressure between ALV and OPV less than the OPV cracking pressure.

Umbilical supply cut, disconnected, crushed.

Symptoms

Surface

Failure of pre-dive checks, Make-Up-Gas contents gauge reads zero. Diver's freeflow/purge check fails.

Dive

Lung squeeze on descent, unable to inject Make-Up-Gas. Auto Air Out not functional. Dry suit inflate not functional.

Recovery action during Dive

Plug in a reserve gas supply. Inflate lungs with manual O2 inject if above 6m.

Abort dive without descending.

Preventative action

Pre-dive checks.

Functional Safety Implication

System should monitor Make-Up-Gas pressure. Where a mismatch, the error message should be specifically "Make-Up-Gas Tank Valve is Closed. Open it!" Requires a contents gauge on the Make-Up-Gas tank.

7.2 Make-Up-Gas Cylinder Switched Off

Cause

Valve rubbed, or forgetfulness.

Symptoms

Surface

Failure of pre-dive checks, Make-Up-Gas contents gauge reads zero.

Dive

Lung squeeze on descent, unable to inject Make-Up-Gas. Auto Air Out not functional. Dry suit inflate not functional.

Recovery action during Dive

Open valve.

Preventative action

Pre-dive checks.

Functional Safety Implication

System should monitor Make-Up-Gas pressure. Where a mismatch, the error message should be specifically "Make-Up-Gas Tank Valve is

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Closed. Open it!" Requires a contents gauge on the Make-Up-Gas tank. Force user to inject Make-Up-Gas in pre-dive check.

7.3 Make-Up-Gas First Stage Failure

Cause

Wear, corrosion or structural failure.

Symptoms

Surface

Failure of pre-dive checks, Make-Up-Gas contents gauge reads zero.

Dive

Lung squeeze on descent, unable to inject Make-Up-Gas. Auto Air Out not functional. Dry suit inflate not functional.

Recovery action during Dive

Plug in a reserve gas supply. Inflate lungs with manual O2 inject if above 6m.

Preventative action

Service correctly and pre-dive checks.

Functional Safety Implication

1. System should monitor Make-Up-Gas pressure. Where a mismatch, the error message should be specifically "Make-Up-Gas Tank Valve is Closed. Open it!" Requires a contents gauge on the Make-Up-Gas tank. Valve unlikely to fail totally and suddenly.
2. System should detect a rapid drop of pressure.

7.4 Make-Up-Gas First Stage Over Pressure

Cause

- Wear of regulator.
- Poor maintenance of regulator.
- Corrosion, particularly of sintered filters causing breakup of the filter.
- Poor design of regulator.
- Icing of regulator.
- Structural failure of regulator
- Poor adjustment of regulator.
- Foreign material under valve seat from tank or from reverse flow into regulator.
- Wear of valve seat.
- Failure of valve seat.

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Symptoms

Surface

ALVBOV free flow, unwanted BC inflation, depending on configuration.

Dive

Auto air free flow, excessive buoyancy in BC, or dry suit, or ALV.

Recovery action during Dive

Shut down Make-Up-Gas valve. Manually operate when needed (shouldn't need to surface). Consider bailout if alternate supply.

Preventative action

1. Service First Stage regulators annually and check interstage pressure during servicing.
2. Inspect First Stages regularly for signs of corrosion or damage.
3. An over-pressure valve is not required on the make-up-gas cylinder because the ALVBOV will lift if there is an over-pressure.

Functional Safety Implication

1. Outside the eCCR, but the “end to end” clause in Functional Safety encompasses this failure.
2. Apply all of the preventative actions listed above.
3. Fit a sintered bronze filter to the detritus tube in the valve or regulator, to prevent foreign material moving from the the cylinder to under the valve seat Monitor Make-Up-Gas contents and check for leakage pre-dive.
4. For commercial diving manifolds, fit one-way valves and filters to prevent any contamination from being blown back onto the bail-out gas seat.
5. When the over-pressure valve fires, it causes a loud noise, alerting the diver to the failure.

7.5 Make-Up-Gas Hose Leaks

Cause

Wear. Poor maintenance.

Symptoms

Surface

Failure of pre-dive checks. Audible gas escape. Make-Up-Gas contents decreasing.

Dive

Audible gas escape. Make-Up-Gas contents decreasing.

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Recovery action during Dive

Abort dive.

Preventative action

Pre-dive checks and servicing.

Functional Safety Implication

Outside the eCCR, but the "end to end" clause in Functional Safety may encompass this failure. Monitor Make-Up-Gas contents and check for leakage pre-dive.

7.6 Make-Up-Gas Manual Injector Failure

Cause

Poor maintenance.

Failure to plug hose on properly.

Symptoms

Surface

Failure of pre dive checks.

Dive

Loss of gas from loop, flooding of loop.

Recovery action during Dive

Urgent. Reconnect hose or re-screw injector down. Bail out if loop flooded.

Preventative action

Pre-Dive checks.

Functional Safety Implication

Design out by using an ALV. If ALV fails, diver should bail out as there is insufficient volume of breathing gas on descent, detectable as a negative pressure in the loop compared to ambient. Instruct user to bail out.
Requires independent bail-out.

7.7 Wrong Gas In Make-Up-Gas Cylinder

Cause

Cylinder filled wrongly.

Incorrect connection of gas at gas switch.

Incorrect gas switch.

Symptoms

Surface

None with normal pre-dive checks.

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Dive

Problems maintaining set point during descent.

Narcosis if too high an N2 content, or accidental connection of argon.

CNS, if too high an O2 cont

Recovery action during Dive

Abandon dive, or connect alternate Make-Up-Gas source (not likely to notice during dive).

Preventative action

Analyse ALL gases prior to use. Once unit is calibrated you can check the Make-Up-Gas O2 content by doing a Make-Up-Gas flush. This should be added as part of the pre-dive tests.

Perform rigorous pre-dive checks with buddy, and do buddy check of every gas switch.

Stop descent or ascent at any gas switch until buddy confirms correct switch is made.

Functional Safety Implication

1. Monitor gas during descent, and monitor END.
2. Eliminate gas switch blocks.
3. Advise divers not to use gas with a CNS or narcosis risk at the greatest depth likely to encountered on the dive. For example, 16% trimix can be used instead of hypoxic gases, for dives to 90msw.

7.8 Alternate Air Source Free Flow

Cause

Dirt or high Make-Up-Gas interstage pressure.

Symptoms

Surface

Failure of pre-dive checks. Audible gas loss.

Dive

Audible gas loss and bubbles.

Recovery action during Dive

Disconnect Auto Air, or try shaking to reseat things. Consider aborting dive.

Preventative action

Service equipment and pre-dive checks.

Functional Safety Implication

Outwith the eCCR, but covered by “end to end” clause.

Monitor Make-Up-Gas contents.

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7.9 No ALV or ALV Failed Off

Cause

No ALV or ALV tends to free-flow, so user switches it off.

ALV Gas supply off because cylinder valve is turned off, or failure of cylinder valve, or first stage regulator, or intermediate supply hose is kinked.

ALV Supply failure: gas supply exhausted.

Symptoms

Surface

None.

Dive

Incident report by Dr. Mike Gadd, submitted to RebreatherWorld: http://www.rebreatherworld.com/rebreather-accidents-incidents/19356-witness-to-a-fatality.html#post189115

What's so difficult about hitting the manual add? Nothing when your sat at your desk or when doing a gentle descent.

But as a safety feature when muck hits the fan a demand valve will automatically give you enough volume to enable you to breathe when there's an unexpected (not a planned) issue that effects your loop volume (such as rapid descent) It will also facilitate and encourage 'sanity breaths' from nose breathing out at first feeling of CO2 - which I believe is a good safety feature

I once jumped in carrying a large stainless steel axe a crow bar and some slings. Very negative. Unfortunately my adv was turned off and the gear I was carrying obscured my manual add. The tank feeding my wing (and bov) wasn't as the qc wasn't fully connected. As I plummeted down to the depths like a speeding train my CLs collapsed I was totally unable to breathe, unsure as to why my wing wasn't inflating, fumbling trying to find the manual add buried under all the gear/stages i was carrying, my ears were in so much pain you cant imagine. In my stressed state (rapid uncontrolled descent, unable to breathe and ear pain) I simply couldn't locate the manual add or fix the wing inflation issue fast enough. It was most unpleasant. I bailed to OC (which was fun because same qc fed the bov! so at first no gas from bov (which I found interesting) so went for offboard 2nd stage :-)) regained my buoyancy and learnt a good lesson. I was only in 95m of water.....

Then there was the time after a 100m dive when I had to throw the anchor over the pinnacle we'd just dived so we could free float deco under the attached buoy. The descending anchor chain snagged on my stage tank and pulled me rapidly down again. On an Inspo the adv shut off I had to deal with freeing myself from the dropping anchor, manually inject gas or switch on the adv so I could breathe. I couldn't do both at the same time! If the adv had been on I would have had both hands free to focus on the snag.

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*Then there was the time i was so wasted on CO2 that I was laying on the seabed doing an impression of a fish. waiting and not really caring too much about dying. I was unable/uninterested in moving my arms to find and press the manual add - I suspect if my adv had been shut off the extra small effort needed to turn it on would have meant I wouldn't. As it was my adv saved my life as I did the only thing I could be bothered to - breathed out my nose. My adv fired, after a few breaths my mind began to clear to a point I could do a manual flush and get my s**t together....my adv saved my life*

In both the above times not having an adv would have been doable - but it adds stress and task loading to an already stressful and task loaded situation - that's why I think having an adv is better than not

An adv is a simple demand valve - hardly rocket science. It will give you gas when you need the volume automatically. It shouldn't fire unless you have too low a loop volume, it shouldn't fire with normal breathing, it shouldn't fire (too much) if your at different angles...imo it doesn't need to be that light. The only thing worse than not having one, is having one but needing to keep it shut off .

In a separate incident, during test at an independent lab of a Deep Life rebreather, the ALV supply on the rebreather under test was interrupted (cylinder valve seat failure, first stage regulator failed closed, or a kinked gas hose), leading to a 2 bar under pressure of the rebreather. This caused no leakage or damage, but would be dangerous of it occurred during a manned dive. The ALVBOV supply had been plugged in that test.

Recovery action during Dive

Stop descending and ascend to achieve adequate loop volume.

Pressing the purge button on the ALVBOV will usually not help because the ALBOV is unlikely to be at fault: the problem will be the upstream gas supply.

Check gas is on.

Consider aborting dive.

Preventative action

No shut off valve should be fitted to ALVs or BOVs.

Service equipment and pre-dive checks.

Functional Safety Implication

Covered by “end to end” clause.

ALVBOV should not have any means to turn it off, other than turning off the supply cylinder (or umbilical supply).

Duplicate the ALV: e.g. ALV and ALVBOV and provide a means for these to be supplied by separate gas sources on dives with a decompression obligation.

Monitor Make-Up-Gas contents.

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7.10 Counterlungs unable to provide gas

Cause

Counterlungs insufficient volume for diver.

Counterlungs collapse such that gas cannot be supplied to ports on the counterlung.

Counterlungs trapped.

Counterlungs kinked.

Lack of gas channel from where the gas is in the counterlung, to the gas port out of the counterlung.

Counterlungs are flat, that is, not box or tube structures, that are fixed such that the counterlung is under tension preventing it filling.

Counterlungs stick together inside due to inappropriate materials or contamination.

Symptoms

Surface

Diver cannot inhale without ALV firing.

Dive

As on surface.

Recovery action during Dive

Abort dive. Bail-out.

Preventative action

Avoid faults by design.

Functional Safety Implication

1. Counterlungs need to be between 4.5 and 6 litres tidal volume to cater for the largest diver, and also for divers to adjust buoyancy slightly by varying their loop volume. The theoretical volume will always be larger than this, and in some cases, significantly larger.
2. All gas paths in the counterlung need to be protected such that the counterlung cannot block the gas exit ports when partially full, in any orientation of the diver. This generally means a spring mechanism of some sort is needed. The diameter of the spring should be the same as the port otherwise the port may become partially blocked.
3. Counterlungs should be fixed down so they cannot trap themselves or kink, including if the diver chooses to dive with covers off or loses a cover.
4. Counterlung material needs to be of a material that does not stick together when wetted with water.

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7.11 BOV seal leaking, emptying loop volume

Cause

BOV barrel seal leaking.

Expansion or contraction of the DSV, BOV or ALVBOV housing or barrel.

Symptoms

Surface

Breathing from Open Circuit.

Dive

As diver exhales from the rebreather loop, the gas is vented into the water either fully or partially.

Recovery action during Dive

Bail out.

Preventative action

Perform a positive and negative pressure check before the dive.

Functional Safety Implication

Lip seals appear to be the most suitable for this application. Ensure wiping movement is sufficient.

7.12 Flapper Valve Stuck Shut

Cause

Flapper valve fixed shut by sticky detritus.

Symptoms

Surface

Unable to breathe.

Dive

As diver exhales from the rebreather loop, the gas is vented into the water either fully or partially, and the dive cannot inhale.

Recovery action during Dive

Bail out.

Preventative action

Perform flapper valve checks before the dive.

Functional Safety Implication

Lip seals require a very thin seal area to avoid stiction.

User manual should emphasise the need for cleaning after each dive.

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7.13 Foreign Material in Breathing Hoses

See also Fault 11.14 and 11.5

Cause

Plugs added by diver to prevent roaches getting into hoses are accidentally left in place.

Symptoms

Surface

Unable to breathe.

Dive

As diver exhales from the rebreather loop, the gas is vented into the water either fully or partially, and the dive cannot inhale.

Recovery action during Dive

Bail out.

Preventative action

Perform full hose flapper valve checks before the dive.

Functional Safety Implication

Ensure seals are available for relevant countries which cannot be left on accidentally.

7.14 Breathing Hoses Kinked

See also Fault 11.11

Cause

Poor breathing hose design.

Symptoms

Surface

Unable to breathe.

Dive

As diver exhales from the rebreather loop, the gas is vented into the water either fully or partially, and the dive cannot inhale, or vise-versa.

Recovery action during Dive

Bail out.

Preventative action

Use non-kinking hoses.

Functional Safety Implication

Ensure hoses cannot kink under any plausible condition.

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8 LOOP VOLUME RELIEF FAILURES

OPV refers to the loop over pressure valve. Burst disk or intermediate pressure over-pressure valves are considered under oxygen supply failures.

8.1 OPV diaphragm damaged

Cause

OPV diaphragm torn or displaced.

Symptoms

Surface

Pre-dive positive pressure check failure.

Dive

Gurgling and other signs of water in loop. Breathing resistance.

Recovery action during Dive

Bail out.

Preventative action

Inspect OPV diaphragm regularly during dive checks.

Functional Safety Implication

Active control over pre-dive positive pressure checks indicated.

8.2 OPV diaphragm folded causing flood

Cause

OPV diaphragm of improper type or design, with sudden pressure change such as with diver entering the water.

Symptoms

Surface

None.

Dive

Gurgling and other signs of water in loop. Breathing resistance. CO2 hit.

Recovery action during Dive

Bail out.

Preventative action

Ensure OPV diaphragm does not fold and remain deformed under conditions of extremely high gas flow, or gas pulses.

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Functional Safety Implication

OPV needs to be fully characterised.

Example Incident

http://www.rebreatherworld.com/rebreather-accidents-incidents/20066-why-c02-scares-dave-incident-report-2.html#post194733

8.3 Foreign material trapped under OPV diaphragm

Cause

Diving in silt, poor maintenance.

Symptoms

Surface

May appear in a pre-dive positive pressure check.

Dive

Gurgling and other signs of water in loop. Breathing resistance. CO2 hit.

Recovery action during Dive

Bail out.

Preventative action

Wash out loop between dives, allowing water to flow out of OPV.

Functional Safety Implication

OPV needs to be fully characterised, including in presence of silt.

Most OPVs are single membrane: a dual membrane would be much safer, with a filter on both inside and outside.
Fit a filter to both inside and outside the OPV membrane/diaphragm.

Example Incident

http://www.rebreatherworld.com/ouroboros-rebreathers/19877-opv-mods-options-ideas.html#post192902

8.4 Incorrect O-ring tolerance

Cause

Poor O-ring groove tolerance or design.

Symptoms

Surface

May appear in a pre-dive positive pressure check.

Dive

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Gurgling and other signs of water in loop. Breathing resistance. CO2 hit.

Recovery action during Dive

Bail out.

Preventative action

Design and manufacture O-ring groove to be within tolerance specified by manufacturer, e.g. Parker O-Ring Handbook.

Functional Safety Implication

1. Check all O-ring designs as part of mechanical design review checklist.
2. Consider the effects of ring deformation under pressure.
3. Consider the effects of thermal expansion or contraction of the surface the O-ring is sealing.
4. Consider lip seals.
5. Make O-rings as thick as possible within ALARP and the ergonomic considerations for that O-ring.

Example Incident

http://www.rebreatherworld.com/ouroboros-rebreathers/19877-opv-mods-options-ideas.html#post195284

8.5 OPV stuck shut

Cause

Poor design or poor maintenance. In some cases, mal-adjustment by diver.

With valve accessible externally, it may be moved accidentally by rubbing with hawsers or ropes.

Symptoms

Surface

Should show up in the pre-dive check, as O2 is added to the system it will not vent normally.

Dive

Breathing resistance. CO2 hit.

Recovery action during Dive

Reset the valve to correct position, and if that does not work, then bail out.

Preventative action

Position valve so it cannot be adjusted accidentally during dive.

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Check OPV cracking pressure as part of pre-dive checks (checking loop does vent with reasonable pressure).

Functional Safety Implication

Locate valve where it cannot be changed accidentally during dive.

During testing, it was found that some housings are very much more liable to be adjusted than others.

8.6 OPV stuck open

Cause

Poor design or poor maintenance. In some cases, mal-adjustment by diver.

With valve accessible externally, it may be moved accidentally by rubbing with hawsers or ropes.

Granular scrubbers have resulted in a granule becoming stuck in the OPV during the dive, with serious close-miss mishap as a result.

Symptoms

Surface

Should show up in the pre-dive check, positive pressure test.

Dive

Venting gas continuously, or on every breath.

Water ingress, Breathing resistance. CO2 hit.

Recovery action during Dive

Reset the valve to correct position, and if that does not work, then bail out.

Preventative action

Position valve so it cannot be adjusted accidentally during dive.

Check OPV cracking pressure as part of pre-dive positive pressure check.

Functional Safety Implication

Locate valve where it cannot be changed accidentally during dive.

8.7 OPV cracking pressure relative to diver changes with attitude

Cause

Incorrect placement of OPV.

Symptoms

Surface

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None.

Dive

Loop volume changes as a function of diver attitude, as does Work of Breathing, OPV may vent or freeflow in some positions.

Recovery action during Dive

Avoid positions causing free-flow.

Preventative action

Position the OPV as close to the lung centroid as possible.

Functional Safety Implication

Ensure correct OPV position.

8.8 OPV housing failure

Cause

Flimsy OPV.

Symptoms

Surface

None.

Dive

OPV comes apart during dive.

Recovery action during Dive

Bail out.

Preventative action

Position the OPV so it is not exposed. Design and manufacture housing from a tough material of sufficient thickness to withstand diver abuse.

Functional Safety Implication

Ensure OPV is robust.

8.9 OPV fails to shut sufficiently for positive pressure check

Cause

Poor OPV design.

Symptoms

Surface

Positive pressure check vents via OPV too readily.

Dive

None.

Recovery action during Dive

None.

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Preventative action

Replace OPV with a design that can maintain a 300mbar pressure when fully shut.

Functional Safety Implication

Verify OPV operation.

8.10 OPV interacts with water drain

Cause

Use of an OPV as a water drain in addition to fitting a normal loop volume OPV.

Symptoms

Surface

None.

Dive

Free-flow.

Recovery action during Dive

Avoid positions causing free-flow, abort dive.

Preventative action

Do not use an OPV as a water trap that is additional to main OPV: they cannot both work unless adjustment is within an extremely tight tolerance.

Functional Safety Implication

Do not use OPVs as water traps: use good water blocking and the main OPV instead.

8.11 OPV is on exhale CL instead of inhale CL where it should be

Cause

Bad design: failure to carry out full verification and testing.

User can swap OPV with ALV in error.

Symptoms

Surface

None.

Dive

In an uncontrolled ascent, gas travels from inhale CL through scrubber to exhale CL, as well as from inhale CL to diver. This gas movement carries all the injected O2 into the exhale CL, where it is vented. As a result the PPO2 in the gas breathed by the diver plummets.

Recovery action during Dive

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Slow ascent.

Empty the inhale CL by deep breath and vent, regularly during ascent.

Preventative action

Locate OPV on inhale CL only.

Functional Safety Implication

Ensure user cannot switch OPV with ALV accidentally.

8.12 OPV is set incorrectly

Cause

Variable setting OPVs.

Symptoms

Surface

None.

Dive

Freeflow or excessive loop pressure.

Recovery action during Dive

Abort dive, or vent manually through the nose (if excessive loop pressure).

Preventative action

OPV should not be adjustable.

Functional Safety Implication

OPV should have fixed pressure, e.g. 35mbar.

8.13 OPV or drain admits water as it operates

Cause

Single membrane OPV.

Symptoms

Surface

None.

Dive

Gradual flooding, or loss of loop gas.

Recovery action during Dive

Abort dive.

Preventative action

Avoid by design.

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Functional Safety Implication

OPV and all valves venting the loop should have one way valves, and be double valves.

8.14 Lack of means to vent loop manually when bailed out

Cause

No manual water dumps or manual venting fitted

Symptoms

Surface

None.

Dive

After bail-out, considerable increase in positive buoyancy during ascent.

Recovery action during Dive

Deliberately flood the breathing loop, e.g. by opening DSV.

Preventative action

Avoid by design.

Functional Safety Implication

All rebreathers must be fitted with a means to vent the loop manually following bail out, for example a water dump with manual activation.

All safety requirements relating to water dumps shall be included.

9 CONTROLLER AND INFORMATION FAILURES

9.1 Battery Low

Cause

Over-use, or internal failure, lack of charge.

Symptoms

Surface

Low Bat warning on monitoring or control device. Solenoid not functioning. Cannot maintain set point.

Dive

Low Bat warning on monitoring or control device. O2 Injector not functioning. Cannot maintain set point.

Recovery action during Dive

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Abort dive. Variable orifice valve should maintain PPO2 if ascent rate is slow, otherwise activate Auto Bail-out and Shut Off valve.

Preventative action

Pre-Dive checks and measure battery voltage before dives. Recharge when warning is shown or before big dive.

Fault incidence reduced by design: O.R. submission includes 3 independent power sources, two of which are maintained at 1 ATM.

Functional Safety Implication

Lack of power is the Achilles Heal of electronics. Provide 3 power sources, with different drain rates, and do not allow dive unless adequate capacity (10 hours minimum).

See all actions for Battery Failure below.

9.2 Battery Failure

Cause

Over-use failure: recharge cycles.

Water in battery compartment.

Lack of cell balancing.

Lack of bad cell detection

Absence of high or low thermal shutdown for charging or discharge.

Absence of charge over-current protection.

Absence of discharge over-current protection.

Symptoms

Surface

No monitoring or control device.

Dive

No monitoring or control device. Solenoid not functioning. Cannot maintain set point.

Recovery action during Dive

Slave should take over. Abandon dive. If both fail then bail out if you have no alternative means of monitoring PPO2.

Preventative action

Pre-Dive checks and measure battery voltage before dives.

Functional Safety Implication

Lack of power is the Achilles Heal of electronics. To address at SIL 3, requires:

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a. Monitor of recharge cycles, to indicate battery service required before battery reaches recharge cycle lift.
b. Water in battery compartment: protect by conservative seal design.
c. Cell balancing, where multiple cells are used.
d. Bad cell detection, particularly where multiple cells are used: cells should not be simply connected in parallel.
e. High and low thermal shutdown for charging or discharge: battery capacity is higher at low temperature for most lithium chemistries, so charging at a low temperature the charge shall stop at the capacity the battery would have at high temperature, otherwise the excess charge results in over-heating of the battery when the battery is warmed up.
f. Charge over-current protection.
g. Discharge over-current protection.
h. Battery state shall be shown during power-up sequence and operation.
i. Provide 3 power sources for SIL-3, with different drain rates, and do not allow dive unless adequate capacity (10 hours minimum).
j. Provide fail safe PPO2 injection in eCCRs that does not require power, e.g. ALVBOV or needle valve or variable orifice – not a normally closed solenoid.
k. Provide failure evident indication, e.g. diver reinforcement of active states using a device that requires regular attention to prevent an alarm state.
l. Provide buddy display, and warning of failure on buddy display.
m. Where

9.3 Power Drop-out or Battery Bounce

Cause

Poor battery and contact design. Manifest when entering water by an automatic bail out device fails due to lack of power, ensure diver can operate it manually, and the failure is evident. rolling backwards on to turtle shell. Momentarily disconnects batteries.

Battery failure.

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Symptoms

Surface

None.

Dive

Hanging. "Dive Now?" message and "Waiting for Data" messages.

Recovery action during Dive

Urgent. Perform start-up cycle. DO NOT CALIBRATE.

Preventative action

Design out the problem.

Always check monitoring or control devices immediately after entering water.

Functional Safety Implication

1. Battery contacts cannot meet Functional Safety. Design out the problem by using multiple redundant rechargeable Lithium Ion Gel batteries, soldered in.
2. Test using swept power drop out, with drop outs from 1us to the time interval needed to activate the Brown Out Circuit.
3. In particular, where there is a master, it SHALL NOT have only one power source. Sudden failure of any single power source occur with too great a frequency to assume that a slave function will take over.

9.4 Battery life error

Cause

Error in calculation of battery life causes dive to proceed when there should have been no dive.

Symptoms

Surface

None.

Dive

Sudden power loss.

Recovery action during Dive

Bail out.

Preventative action

Eliminate risk by design.

Functional Safety Implication

Batteries shall be properly characterised for diving applications, including the error in predicting battery life quantified.

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Secondary cells shall not be used: they cannot be characterised as they are generally supplied by many different companies, each with slightly different characteristics.

There shall be at least two power sources for SIL-2, and three at SIL-3. Each have to be checked, and the dive does not start if one of them is down: this can be achieved by signalling to an auto-shut off valve for example.

There is a risk that where the cell has a very long life, e.g. the equipment can operate for hundreds of hours between recharges, then the user does not check the battery level. The optimum period appears to be around 30 to 40 hours between recharges.

9.5 Battery overheating

Cause

Shorting or mechanical damage to the battery.

Excessive discharge rate.

Excessive charge rate.

Charging in a temperature range where the battery has a higher capacity than at a temperature which occurs during subsequent storage, transport or use.

Symptoms

Surface

Fire or Explosion risk.

Dive

Explosion risk.

Risk of sudden loss of battery power.

Recovery action during Dive

Bail out.

Preventative action

Eliminate risk by design.

Functional Safety Implication

i. Some battery types are much more liable to overheat or explode than others: for example, Lithium cobalt cells can explode easily, whereas Lithium phosphate cells cannot. Unfortunately the power density of Lithium phosphate chemistry is half that of Lithium cobalt.

ii. Monitor of recharge cycles, to indicate battery service required before battery reaches recharge cycle lift.

iii. Water in battery compartment.

iv. Cell balancing, where multiple cells are used.

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v. Bad cell detection, particularly where multiple cells are used: cells should not be simply connected in parallel.

vi. High and low thermal shutdown for charging or discharge: battery capacity is higher at low temperature for most lithium chemistries, so charging at a low temperature the charge shall stop at the capacity the battery would have at high temperature, otherwise the excess charge results in over-heating of the battery when the battery is warmed up.

vii. Charge over-current protection.

viii. Discharge over-current protection.

ix.

x. The risk of cells being shorted is very much higher in a marine application than on land applications.

xi. Where the cell is large enough to cause rupture of a housing (equivalent to an AA cell or larger), the only viable solution is to use Lithium phosphate cells, e.g. Valence Saphion cells.

xii. An alternative solution for very low applications is to use Lithium mixed oxide cells smaller than AA of a shape that ruptures easily, for example very thin panel cells, with a means to control the energy release, such as immersion in silicone oil with an expansion bladder, or potting in PU and silicone gel.

xiii. Lithium cobalt cells should not be used in any configuration.

9.6 Monitoring or control device failure not apparent to user

Cause

Flooding, wiring or mechanical breakage.

Symptoms

Surface

Blank screen.

Dive

Blank screen, frozen screen.

Recovery action during Dive

Main controller should take over: check this occurs. Abandon dive.

Preventative action

Protect monitoring or control devices and check wiring during service.

Functional Safety Implication

1. Perform full JTAG testing during power-up sequence.

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2. Use multiple devices in monitoring or control device, so failure of one clock or one integrated circuit should not cause loss of monitoring or control device.
3. Provide a PFD in addition to monitoring or control device.
4. Base unit should be made to at least automative SQA 9002 standards and controls.
5. All electronics and software should meet EN 61508:2004 Parts 1 to 3 to at least SIL 2.

9.7 Monitoring or control device Hangs

Cause

Incompetent design: single processor, single clock source, single power source, no heartbeat monitor (watchdog circuits), no brownout circuit.

Symptoms

Surface

Screen should not change.

Dive

Screen should not change, no alarms.

Recovery action during Dive

Bail out.

Preventative action

Problem should be eliminated by design.

Functional Safety Implication

1. This is a problem that occurs with some monitoring or control devices examined during FMECA studies of contemporary equipment. The normal design procedures applied for safety critical systems should prevent this. The system should check automatically during normal start-up that these safety design provisions are operating correctly.
2. Ensure Watchdog circuit is operating by halting the clock for the Watchdog period.
3. Ensure Brown-Out circuit is operating by power cycle test.
4. Ensure state machines have redundant states to detect failure and return unit to safe operation.
5. Fill all unused memory locations with recovery code.
6. Routines should apply predicates in input data so that random jumps to the routine can be detected and recovered.
7. The start-up sequence should detect if an abnormal shutdown occurs, so immediate recovery can be carried out.

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8. Any such failure should be logged and the unit permanently locked out on the surface.
9. The circuit should have multiple clocks, power supplies and other circuits so that the MTBCF of the circuit exceeds the SIL 3 requirement by sufficient margin to ensure that, when coupled with the MTBCF of the mechanical components, the overall MTBCF is still above 1 billion hours.

9.8 Monitoring or control devices switched off

Cause

Design fails to keep monitoring or control devices switched on when unit is being used.

User often switches monitoring or control device off if it fails in an obvious or dangerous manner underwater. For example, if keeps injecting O2 despite PPO2 being sufficient, or enters calibration mode.

Be very careful to analyse all failures where user surfaces with monitoring or control devices switched off, especially with experienced users.

Symptoms

Surface

Pre-dive check failure. Blank monitoring or control devices. No pre-breathe.

Dive

No monitoring or control device display.

Recovery action during Dive

Bail out or die.

Preventative action

Pre-dive checks and basic monitoring of unit.

Functional Safety Implication

1. Occurs in units where there is a failure of the electronics and user switches the monitoring or control device off to try and bring the unit back up. Several cases where user has died before unit has come back up.
2. Solution adopted is to design out the problem: ensure unit powers on automatically whenever the PPO2 is less than 0.16.
3. Eliminate all possibility that the unit can “hang”.
4. Provide an PFD which also switches on automatically when PPO2 is less than 0.16, and cannot switch off when unit is under pressure or is being breathed from.

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5. Functional Safety requirements would demand monitoring or control device switches on automatically when unit is used.

9.9 Oil Filled Chamber Leaks Oil

Cause

Mechanical damage.

Poor servicing or maintenance.

Reservoir piston to accommodate thermal expansion is stuck.

Reservoir for thermal expansion is too small.

Symptoms

Surface

Filling oil visible inside unit.

Dive

Smell of the filling oil inside the loop.

If the pressure sensor is inside the oil-filled volume, it will show a lower (smaller) depth than is the actual depth.

Recovery action during Dive

Bail out.

Preventative action

Check unit for signs of leakage.

The leakage is usually obvious: an oil film outside the rebreather, that causes an oil film on the water when the unit is washed.

Functional Safety Implication

6. Use of hydrocarbon filling oils is a dangerous practice and not recommended as they can contaminate the breathing loop.
7. Use of waxes (solid paraffins) causes serious problems with thermal expansion, and act as insulators which can cause components to overheat.
8. Loss of oil as a failure could be detected using a differential pressure sensor, but this is an expensive solution that is prone to failure due to the thermal expansion of the oil.
9. One solution is to use food grade silicone oil to avoid a health hazard, and to remove all components liable to offgas from the oil-filled volume (moving them to a 0ATM or 1ATM compartment in the sea water). Silicone oil has a high rate of thermal expansion (up to 10% of its volume over the operating range of the equipment, so a bladder, bellows or diaphragm shall be fitted to allow the expansion).
10. Consideration should be given to adding a perfume to the filling oil, so any leakage is apparent from the smell in the loop: to date, no

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suitable perfume has been found that does not cause a reaction to some people when concentrated under pressure.

11. The current solution used in the Open Revolution project is to use a non-setting PU gel instead of silicone oil, as the expansion of a gel is considerably less than oil, and the ingress of small amounts of water does not lead to an immediate failure.

9.10 Electronic Component Explodes

Cause

Use of inappropriate components.

Failure becomes critical if component is not completely separated from the breathing loop.

Symptoms

Surface

Odour inside breathing loop.

Dive

One-off noise.

Odour inside breathing loop.

Recovery action during Dive

Bail out.

Preventative action

Eliminate risk by design.

Functional Safety Implication

1. Perform full self-test on power up.
2. Eliminate all components liable to explode (tantalum or electrolytic capacitors, all components incorporating a gel or a gas, all components incorporating an electrolyte).
3. Components that cannot be eliminated, such as the batteries, to be moved to a 1 ATM environment outside the rebreather, that can physically withstand the pressure rise from the component being vapourised. That is, the 1 ATM environment should withstand the vapour pressure from boiling off the electrolyte.

9.11 Controller fails to handle situation where diver does not understand failure message or is unable to act

Cause

User does not understand the warning.
User is injured and not able to actuate unit, e.g. CNS toxicity.
User is entrapped by netting or cable limiting mobility.

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Failure of back light on monitoring or control device where user relies totally on the monitoring or control device and is using the monitoring or control device in a dark environment.
Failure of voice annunciation system where user relies totally on the voice annunciation.
Failure of buzzer, where user relies totally on buzzer.
Failure of Head Up Display.

Recovery action during Dive

Read the warning message, using a torch if necessary. If not clear, bail out.

Preventative action

Proper design procedures.
Proper maintenance and training.

Functional Safety Implication

- Provide a reference: in the Open Revolution submission this is the text display under the main monitoring or control device display. This displays the failure and the action required. If in doubt the user can look to this display and receive succinct instruction on how to correct the problem, and its significance.
- Provide multiple annunciation: the four above are included in the sports rebreather configuration – in the commercial diving configuration the monitoring or control device functions move to a topside console.
- Provide an automatic bail-out valve so user cannot ignore critical actions.

9.12 Faulty Software by design

Cause

Design not compliant with Functional Safety.

Symptoms

Surface

Any software malfunction, including hanging or jumping between states

Existence of states where software does not maintain life.

Dive

As per surface symptoms.

Recovery action during Dive

Bail out.

Preventative action

Ensure design meets Functional Safety.

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Functional Safety Implication

1. Software that does not maintain a PPO2 setpoint in some modes is incompetent and does not meet basic safety requirements let alone Functional Safety
2. The industry is using software where nothing is verified, (non-verified code, compiled with buggy compiler, running on non-verified processor in poor hardware environment). Even normal practices for non-safety-related software, such as automated GUI checks, are not applied.
3. No software or hardware control meeting Functional Safety should encounter these issues at a safety critical level. The software should be formally verified.

9.13 Faulty Software by ageing

Cause

EPROM, Flash memory or DRAM corrupted by charge decay over time, or by alpha particules.

Symptoms

Surface

Any software malfunction, including hanging or jumping between states.

Existence of states where software does not maintain life.

Dive

As per surface symptoms.

Recovery action during Dive

Bail out.

Preventative action

Ensure design meets Functional Safety.

Functional Safety Implication

Software needs to be fail safe, including a code CRC check as part of startup sequence.

9.14 Monitoring or control devices Misread

Cause

Poor visibility in halocline or thermocline, with small font-size on monitoring or control devices.

Lack of back light.

Symptoms

Surface

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Error in reading monitoring or control device.

Dive

Error in reading critical information on monitoring or control device.

Recovery action during Dive

Check monitoring or control device more carefully.

Preventative action

Check monitoring or control device carefully.

Functional Safety Implication

The main monitoring or control device should have the largest display which it is practical to carry.

Large displays carry an increased risk of damage due to being dropped or mishandled. Suitable materials should be chosen to minimise this risk.

Displays should be backlit.

9.15 Cracked Electronics Housing

Cause

Housing subject to excessive mechanical stress, before dive or from pressure.

Inappropriate materials or stresses in monitoring or control device design.

Symptoms

Surface

Electronics malfunction.

Dive

Any electronics malfunction.

Recovery action during Dive

Bail out.

Preventative action

Service correctly and pre-dive checks.

Functional Safety Implication

1. This problem occurs with electronics, particularly monitoring or control devices that are not Functional Safety compliant.
2. If the monitoring or control device has two sets of electronics, then a failure of any one part should not cause failure of the whole. This is a natural product of any design meeting SIL 4.
3. The electronics should perform a JTAG test on start-up: this would identify the problem prior to dive.

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9.16 Corroded wiring

Cause

Caustic cocktail.

Unit left in flooded condition.

No, or inadequate, conformal coating to wiring.

Use of inappropriate cable, such as non-plated cable.

Symptoms

Surface

Electronics malfunction. Visible corrosion.

Dive

Any electronics malfunction.

Recovery action during Dive

Bail out.

Preventative action

Service correctly and pre-dive checks.

Functional Safety Implication

This problem occurs with electronics that are not Functional Safety compliant.

The electronics should perform a JTAG test on start-up: this would identify the problem prior to dive.

9.17 System Looping on Interrupts, raising PPO2

Cause

FMECA on a contemporary system: no battery level indicator, using primary cells (i.e. user replaceable), where the monitoring or control devices resets over and over if the battery is low and the monitoring or control device will fire the solenoid every time it resets.

Preventative Action

Competent design.

Functional Safety Implication

1. Consider effect of watchdog timers and brown out circuits firing repeatedly, blocking other actions.
2. NASA Software Safety Guidelines, Functional Safety and ISO 12207 recommends avoidance of interrupts in Cat A/High SIL safety systems. Any departure from that recommendation should be fully supported by a detailed safety case and verification.

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9.18 High Voltage on Connectors

Cause

Poor EMI, with static discharge. Up to 25KV static discharge can occur in operational environments, especially if rebreather is on a trolley or conveyor before being touched or contacting an earthed metal object.

Connectors that carry power and signal, e.g. commercial rebreathers where there is 24V umbilical power and twisted pair for data. Water gets into connector (such as when they are unplugged), shorting 24V to signal.

Symptoms

Surface

Loss of data.

Dive

Loss of data, which in a poor design could propagate.

Recovery action during Dive

Return to bell, or bail out.

Preventative action

Separate power and data, protect data lines from direct connection to highest voltage power source used in connection with the equipment.

Functional Safety Implication

Requires unusually high degree of data line protection.

9.19 Brown out cycling

Cause

Brown out circuit activated, rebreather restarts causing increase in power consumption, causing repeated brownout.

Symptoms

Surface

Can fail to inject O2.

Dive

Ditto

Recovery action during Dive

Bail out.

Preventative action

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Design out the problem.

Use fail safe injectors, and put into safe mode on detecting brown out or power down: requires sufficient capacitance to operate valve.

Functional Safety Implication

Requires design verification of this failure mode, and cycling of brown-out events.

9.20 Failure to turn on

Cause

Design error: failure to use an appropriate safety critical architecture, such as TTA.

Note this fault Is also covered elsewhere.

Symptoms

Surface

Diver is breathing from equipment that is turned off. Diver passes out.

Dive

Ditto but diver drowns.

Recovery action during Dive

Inject gas immediately.

Preventative action

Design out the problem.

Rebreathers need to switch on automatically with falling PPO2.

Functional Safety Implication

Requires an auto-on feature to turn unit on, preferably automatic switch on with falling PPO2. See also Fault 9.25

9.21 Single points of failure

Cause

Design error: a single short, open or component failure, causes controller failure leaving it in a unreasonably dangerous state.

Symptoms

Surface

Hung controller.

Dive

Ditto but diver drowns.

Recovery action during Dive

Inject gas immediately, bail out.

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Preventative action

Design out the problem.

Use a competent safety architecture.

Functional Safety Implication

MTBCF required for entire electronics system. Pay special attention to connectors, where any signal may be shorted to any signal by water. For example, power may be applied to low level signal lines.

9.22 EMC failure

Cause

Design error: failure to protect design from sufficient Electro-Static Discharge (ESD), conducted transients, RF fields, or magnetic field.

In commercial diving, divers report teeth fillings overheating if an earthing clamp is detached during cutting operations due to the induced field intensity, despite the diver's head being inside a helmet.

Symptoms

Surface

Hung controller, jump to unexpected state, I/O lines not functioning normally

Dive

Ditto.

Recovery action during Dive

Inject make-up-gas immediately to a known PPO2 in the breathing loop, bail out if controller then behaves unexpectedly.

Preventative action

Determine appropriate EMC requirements and design out the problem.

Use a competent safety architecture and validate it effectively under the range of EMC conditions.

Functional Safety Implication

EN14143:2003 Section 5.13.3 requires the rebreather meet EN 61000-6-1. This is very poorly worded, as EN 61000-6-1 covers a wide variety of tests and it is not clear which tests apply.

RF Field Immunity, Magnetic Field immunity and cable Transient Surge Tests: as these are a legal requirment, those tests need to be carried out by an accredited ISO 17025 laboratory, appointed by an ILAC registered body. All other tests can be carried out in a traceable and witnessed manner: some are specialised.

The following Immunity and Susceptibility test requirements are applied to Deep Life designs:

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1. EN 61000-6-3:2007 Radiated Emissions
2. EN 61000-6-3:2007 Conducted Emissions
3. EN 61000-3-2:2006 Powerline Harmonics
4. EN 61000-3-3:2005 Powerline voltage fluctuation and flicker
5. EN 61000-4-2:2001, ESD Immunity to requirement EN 61000-6-1:2007 Criteria B (8KV air, 4KV contact ESD)
6. EN 61000-4-3:2006, RF Field Immunity to requirement EN 61000-6-1-2007 Criteria A 3V/M, 80MHz to 1GHz
7. EN 61000-4-4:2006, Electrical Fast Transient/Burst (EFT) to requirement EN 61000-6-1-2007 Criteria B
8. EN 61000-4-5:2005, Electrical Slow Transient (Surge) Immunity to requirement EN 61000-6-1:2007 Criteria B
9. EN 61000-4-6:2006, RF Conducted Immunity to requirement EN 61000-6-1:2007 Criteria A
10. EN 61000-4-8:2001, Magnetic Field Immunity to requirement EN 61000-6-1 Criteria A 3 A/M, 50 and 60 Hz
11. EN 61000-4-11:2004, Voltage Interruption Immunity to requirement EN 61000-6-1:2007, Criteria B and C
12. FCC Part 15, Subsection A
13. A 30,000 Amps per square meter DC test shall be applied to all electronics in view of the extremely high current environment in underwater welding and cutting operations.
14. A review of processor susceptibility has resulted in a conclusion that power disturbance susceptibility shall be assessed using a full sweep of full scale power interrupts shall be applied from 100us to 1s in 50us increments, without malfunction to supplement electrical transient tests.
15. A full sweep of brownout conditions for all power supply combinations shall be applied.
16. A full sweep of power noise from 1us to 100us shall be applied in 1us increments.
17. All units with power supplied by cables longer than 10m shall have a 500VDC pulse applied to the power supplies, in accord with ship electronics regulations, including diver umbilicals

No malfunction shall be observed under any of the above conditions.

All self contained electronic assemblies shall be tested (rebreathers, monitors, PFD, bell boxes and communications units).

The minimum legal requirement is testing for Radiated emissions, ESD, Auto-Bail Out failure to operate

9.23 Auto-Bail Out fails to operate when required

Cause

Mechanism jam, electrical failure, freezing, free-flow, high ambient temperatures reduce energy available to drive the actuator, sliding surfaces

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stick, wear of actuator or related parts, mechanical damage, corrosion, salt deposits, failure to service, failure to lubricate, parts out of tolerance, firmware failure.

Symptoms

Surface

Failure of safety function to operate.

Dive

Ditto.

Recovery action during Dive

Operate bail out valve manually.

If free-flow, bail out to another regulator or feather the cylinder valve.

Preventative action

Mitigate by design.

Functional Safety Implication

The DL ALVBOV electro-mechanical actuator was designed for intermittent operation. However, in the period 2011 to 2013, the continuing accident monitoring identified the need for the actuator to be able to operate on a continuous basis.

The accident study information involved a respected rebreather manufacturer who promote a fully automated recreational rebreather. The market for that rebreather is primarily divers who would normally use Open Circuit SCUBA. A series of fatal accidents and safety incidents have occurred where the diver wilfully ignored warnings from the rebreather. The incidence of those mishaps is considerably higher than that of comparable accidents in the technical diving community from 1995 to 2010. It is clear from this change in the pattern of accident data since 2010 that the actuator should meet the requirements for a device suitable for continuous operation (used frequently), rather than an intermittent operation device (with useage once a year or less).

To achieve the reliability for a continuous operating device (i.e. used frequently) the design of the system should endeavour to incorporate the following features:

a. Actuator should be implemented with the absolute minimum of moving parts.

b. Actuator shall be protected from user tampering.

c. Separate annunciation (e.g. voice and LEDs) is needed as well as bail out actuator.

d. Ensure diver can reach tank valves in SCUBA applications.

e. Produce bail out valve from durable materials.

f. User manual should require diver to operate bail out manually when a bail out condition occurs, and not to rely on an automatic function.

g. Test the bail out valve during the surface preparation on every dive.

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h. Automatic bail out valve shall be able to be activated manually without any electronic power.

9.24 Auto-Bail Out operates when not required

Cause

Mechanism jam, electrical failure, freezing, free-flow, high ambient temperatures reduce energy available to drive the actuator, sliding surfaces stick, wear of actuator or related parts, mechanical damage, corrosion, salt deposits, failure to service, failure to lubricate, parts out of tolerance, firmware failure, sensor failure, program failure, sensor noise.

Symptoms

Surface

Diver is forced onto bail out gas.

Dive

Ditto.

Recovery action during Dive

Operate bail out valve manually to get back on loop. If that fails, bail out and abort dive.

Preventative action

Mitigate by design and manage by good dive practice: carry sufficient bail out gas

Functional Safety Implication

a. Emphasise the need to carry sufficient bail out gas in diver training.
b. Monitor the rate of false alarms and set alarm matrix values accordingly.
c. Automatic bail out valve shall be able to be activated manually without any electronic power.

9.25 Auto-On Encourages Reckless Diver Behaviour

Cause

Rebreather does not pass predive checks, so diver simply jumps in knowing the rebreather has auto-on.

This fault mode is separated out in this FMECA as a result of an fatal accident on another rebreather model: every rebreather accident is analysed for new fault modes regardless of who makes the rebreather in question – this document is a repository of all known top level rebreather faults, so they are not repeated with new generations of equipment.

Symptoms

Surface

Fails to pass predive checks.

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Dive

Alarms are ignored, as diver knows they relate to missing predive checks.

Recovery action during Dive

Bail out.

Preventative action

Mitigate by design.

Functional Safety Implication

This is a very interesting fault and related to the fault in Section 9.23.

On one hand the diver needs to be protected from hypoxia, as there are many fatal accidents caused by divers diving rebreathers that are switched off on the surface, or underwater, or that are in a non-life support mode underwater, but on the other hand, needs to be protected from himself exploiting this feature when the rebreather is not safe to dive.

It is essential to provide auto-on, given the number of fatal accidents due to the absence of this feature, but to prevent this arrogant fault mode, further safety features are needed that may include :

1. To provide a very low set point such that the diver is going to have very long decompression penalties if he does this: e.g. a set point of 0.3 atm.
2. Auto-on requires an automatic bail out device, so the diver cannot go onto the breathing loop if the electronics concludes it is unsafe to do so.
3. Alarms need to warn buddies clearly that the diver should not dive, such as red displays, red buddy displays, and messages such as “SUICIDAL DIVER, ABORT DIVE!”.
4. Injectors that are under electronic control should be wide open so the diver cannot get off the surface after an auto-on dive, but the injector then needs perform in normal eCCR mode once the rebreather is deeper than the O2 CNS depth limit, moving to a lower PPO2 than normal to penalise the diver.
5. Logs needs to maintain records of all warnings, so after power loss, actions of diver are clear.
6. Provide only low PPO2 alarm in this mode, not the normal PPO2 display to the diver.

9.26 Water Ingress into Electronics

Cause

There are multiple potential causes for water ingress:

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- Seal failure: wrong seal type or hardness, seal damaged, seal has inadequate compression, seal has excess lateral movement, foreign body on seal surface, seal extruded by pressure
- Plastic porosity: many bulk extruded plastics have porous areas in their cross-section, as the plastic contracts as it cools to form a cavity or sponge-like microstructure.
- Deformation under pressure
- Physical damage, e.g. cracks
- Inappropriate cable glands: plastic cable glands in particular can withstand only low pressure differentials. Even BlueGlob glands are limited to 15 bar. Cable glands should be avoided where at all possible: either wires can be run inside pressure hose, or connectors used instead.
- Poor component fit
- Unequal thermal expansion
- Flow lines in moulding

Figure: Example of flow lines in a plastic injection moulding, at x50 magnification. The flow line is caused by plastic flowing around a feature in the mould and rejoining itself, then contracting as it cools, leaving a fine gap. The recess formed by the flow line allows a path for water through the whole body of the plastic. The line itself is just visible to the naked eye.

Symptoms

Surface

Water visible under or on display.

Erratic behaviour.

Watchdogs activated.

Excess power drain.

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Overheating of battery.

Sudden power off.

Dive

As on surface.

Recovery action during Dive

Bail out.

Preventative action

Mitigate by design.

Functional Safety Implication

It is necessary to vary that each possible cause of flood is eliminated in a design, using appropriate design verification tests. A feature of new electronic designs, tends to be repeated flooding during development: each flood needs to be traced and eliminated.

Functional safety mitigation measures may include:

- Use a vacuum inside the housing of dive electronics, and detect when the vacuum is lost, to put the system into a safe mode and shutdown.
- Use of Gel fill such that if there is water ingress the damage is limited. Silicone oil expands by around 10% in volume over the normal operating temperature range for dive equipment so provision needs to be made for that, such as use of a diaphragm, membrane or compensating piston. The amount that gels expand depends on their set viscosity, with high durometer (near solid) gels expanding little, and very viscous gels expanding to a similar degree as silicone oil.

A useful tool in tracing sources of water ingress is Kolor Kut paste: this changes colour in the presence of water.

10 OXYGEN LEVEL MONITORING FAILURES

Control and information failures are considered above: this section is concerned about the oxygen level sensing.

10.1 O2 Cell Decompression Failure

Cause

Differential pressure on O2 cell.

Decompression of O2 cells faster than is safe for a human.

Rupture of rear membrane inside O2 Cell causes KOH to be deposited on to temperature compensation board.

Symptoms

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Surface

Not apparent.

Dive

If the diver flushes the loop, the PPO2 will be different from that expected.

Recovery action during Dive

Bail out.

Preventative action

Careful inspection of sensors. It is unreasonable to expect the user to do this on every dive.

Functional Safety Implication

This is a serious failure in that it causes the O2 Cell reading to fluctuate both high and low depending on temperature.

Clear advice on care and maintenance of O2 Cells shall be in the user manuals for the rebreather, including avoiding rapid decompression, shock, temperature extremes or mechanical damage.

Solution adopted is to change the sensor design to allow this problem to be detected. The temperature compensation circuit is removed and replaced with a 100Ohm load. The electronics check for the existence of the 100Ohm load to verify that the correct sensor type is fitted and the load is there, then tests the cell by charge injection. Only then will it use that sensor reading (otherwise it will report a faulty sensor), and will also report a fault when the cell has a decompression fault because the charge relaxation time will differ significantly from that of a good cell. This method of automatic self test before and during the dive detects the problem and can provide cell screening.

10.2 O2 Cell has CO2 Contamination

Cause

High level of CO2, such as from pre-breathing without a scrubber, causes CO2 to migrate across O2 cell membrane, into KOH, where it converts KOH into water.

Symptoms

Surface

Not apparent.

Dive

If the diver flushes the loop, the PPO2 will be different from that expected.

Recovery action during Dive

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Bail out.

Preventative action

If CO2 level high on start-up, check cells for droop.

Functional Safety Implication

This is a serious failure in that it causes all O2 Cell readings to read low.

This should be detected automatically by doing the O2 flush under start-up sequence control, and hence eliminated.

O2 Cells need to be characterised for degree of droop in CO2 and cells selected that do not suffer from CO2 poisoning. Analytical Industries PSR-11-39-DL sensors tolerate pure CO2 exposure for more than 24 hours, and no CO2 failures found in tests involving multiple exposures to 4.5% SEV CO2 for up to 8 hours at a time at depths to 400m.

10.3 Load Resistor Failure in O2 Cell

Cause

Cell has a load resistor, typically 82 to 390, to bleed off the charge generated by the cell, and convert the charge into a current through the resistor, so the voltage from the cell can be measured. If the resistor becomes open circuit, the output voltage on the cell increases until there is another discharge path. This can create very high voltages with enough power stored in the capacitance of the cell to destroy 10K HBM input protection.

Preventative Action

1. Competent design.
2. Avoid cells with multiple components in the output: more components means a greater failure risk.

Functional Safety Implication

1. Use a connector which always mates ground before signal, and protects the connections from corrosion.
2. Do not wire all cells to one chip, whether one ADC, one MUX or one op-amp block (e.g. a quad op-amp). This affects the redundancy design: there needs to be either four sensors so no more than two are routed to a chip, or three completely independent ADC channels.

10.4 O2 Cell Contamination

Cause

Organic material in O2 Cell KOH solution.

Symptoms

Surface

Drift of O2 Cell readings

Dive

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May manifest as a ceiling fault during the dive.

Recovery action during Dive

Eliminate the sensor from the PPO2 calculation.

Preventative action

Check sensors for drift. Replace sensors that drift.

Functional Safety Implication

Requires that the system check for need for sensor replacement and for sensor drift during successive calibration cycles.

10.5 O2 Cell Thermal compensation failure

Cause

Manufacturing fault, design fault, or component failure in O2 cell.

See also fault 6.28.

Symptoms

Surface

Not apparent.

Dive

If the diver flushes the loop, the PPO2 will be different from that expected.

Recovery action during Dive

Bail out.

Preventative action

Careful inspection of sensors. It is unreasonable to expect the user to do this on every dive.

Functional Safety Implication

1. This is a serious failure in that it causes the O2 Cell reading to fluctuate both high and low depending on temperature.
2. Solution adopted is to change the sensor design to allow this problem to be detected. The temperature compensation circuit is removed and replaced with a 100Ohm load. The electronics check for the existence of the 100Ohm load to verify that the correct sensor type is fitted and the load is there. Only then will it use that sensor reading (otherwise it will report a faulty sensor). This eliminates the problem at source.
3. Essential to ensure the thermistor is properly matched to the oxygen sensor, particular at the point the O2 cell is calibrated. See fault 6.28.

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10.6 O2 Cell Loose Connection

Cause

Corrosion or poor maintenance.

Symptoms

Surface

Intermittent "Out of Range" or "Failure" messages on a cell. Failure to calibrate.

Dive

Intermittent "Out of Range" or "Failure" messages on a cell.

Recovery action during Dive

Make-Up-Gas flush to check other 2 sensors respond correctly. Consider bail out. Abandon dive.

Preventative action

Service carefully.

Functional Safety Implication

Use an SMB connector to minimise risk, by having a connector with multiple contact faces.

10.7 O2 Single Cell Failure

Cause

See full list of O2 Cell failure modes in DV_O2_cell_study_110105.pdf

Symptoms

Surface

Intermittent "Out of Range" or "Failure" messages on a cell. Failure to calibrate.

Dive

Intermittent "Out of Range" or "Failure" messages on a cell.

Recovery action during Dive

Make-Up-Gas flush to check which sensors respond correctly. Consider bail-out. Abandon dive.

Preventative action

Replace cells at correct intervals (every 12 months).

Check linearity and accuracy of cells to 4 atm every 3 months.

Handle cells carefully, keeping away from heat sources, freezing conditions.

Functional Safety Implication

O2 Cells are notoriously unreliable, and the overwhelming majority are wholly unsuitable for use in a rebreather.

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To use galvanic oxygen cells in a rebreather involves a demanding Functional Safety process, that includes:

1. Proper characterisation of the available cells. See an example on the Deep Life web site, www.deeplife.co.uk/or_dv.php as document DV_O2_cell_study_110105.pdf, which catalogues both failure modes and mitigation measures to improve cells.
2. The cell design and manufacture should be optimised for rebreather use, in particular, with sufficiently fast response, accuracy, shock tolerance, water tolerance and be free from vapour trap mechanisms, tolerate CO2, helium, pressure, and in an environment that is subject to rapid temperature changes. Engineer the cells so all failures are in the same direction (low).
3. The O2 cells need adequate calibration and self test circuitry in the rebreather.
4. The cells need a very good temperature compensation algorithm. An example is in the PPO2 Accuracy report on the above Deep Life web site directory.
5. The sensor fusion algorithm needs to withstand multiple cell failures safely. An example of an oxygen cell sensor fusion algorithm in a rebreather is available in the document DV_O2_sensor_fusion_YYMMDD.pdf located in the same directory as referenced above.

If these measures are used, then the PPO2 can be indicated reliably, accurately and be highly tolerant of cell failures.

Some of the examples of poor functional safety design include:

1. Presentation of raw sensor data to the diver without interpretation.
2. Use of an averaging process instead of a sensor fusion algorithm tailored to the cell failure modes.
3. Use of sensors with integral temperature compensation: this can give rise to very large errors from all sensors simultaneously as all sensors are exposed to the same environment and are usually of the same type.
4. Use of voting algorithms. These are not a safe substitute for a properly designed sensor fusion algorithm.
5. Use of cells with ceiling limits that may fall momentarily within the range of PPO2s that occur during diving. After the ceiling has been reached, the cell transfer function often becomes negative, causing catastrophic failure of the PPO2 control system (as increases in PPO2 cause a reduction in cell output): this event has occurred in more than one fatal accident and can be seen in cell characterisation tests, such as Sensor B in the test run overleaf.
6. Use of cells unsuited to rebreather applications. These are often apparent on visual inspection, using Molex type connectors (non-sealing, with a single wiping contact), having a well or pit around the sensing membrane, and simple analogue temperature compensation.

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The rebreather should indicate cell status to the diver, to avoid a reliance on a group of failing or failed sensors.

10.8 O2 Cell Failures Tracked Incorrectly

Cause

Multiple O2 Cell failures with voting logic.

Preventative action

Do not use voting logic.

Functional Safety Implication

Eliminate problem by carrying out a fault assessment of O2 Cell failure modes, then test of O2 Cells to a Test Plan to verify those modes.

Use sensor fusion algorithm that can detect one good sensor among faulty sensors.

Provide means to check sensors automatically when a sensor failure occurs, such as injecting a known quantity of O2. This requires a calibrated O2 injector: this can be done automatically during pre-dive checks.

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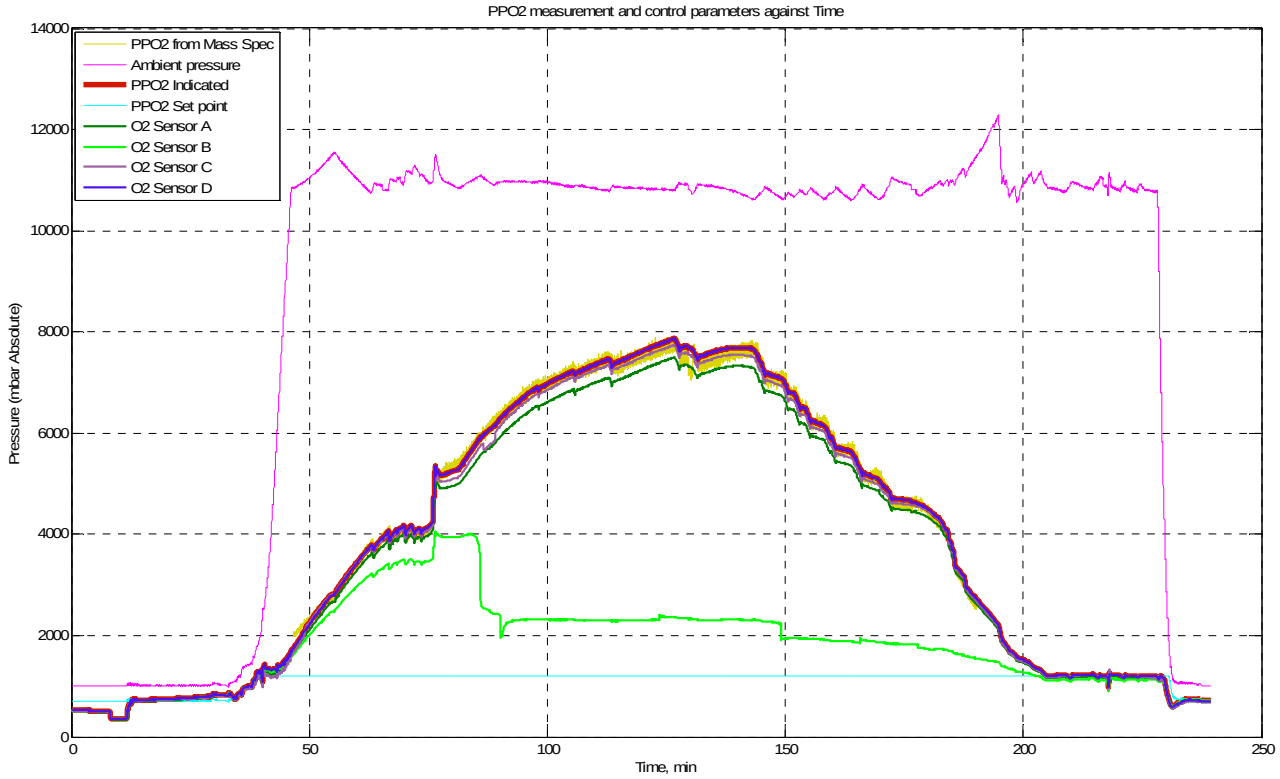

Figure 10-1. Example of good functional safety behaviour during a test dive, to 100m depth. The four O2 cells are 2 years old yet the indicated PPO2 matches that of the mass spectrometer almost perfectly throughout the dive. The PPO2 monitor using these cells shows it is accurate to a PPO2 of at least 7.8 atm (well beyond that which may occur in diving), except one (Sensor B) which fails with a classical ceiling fault (current limiting) shortly after the descent. The less accurate sensors are rejected immediately by the sensor fusion system. The small ticks in the response is the oxygen injector self test, which is also used to test the sensors.

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10.9 O2 Two Cell Failure

Cause

Exhausted or out-of-date cells. Insufficient ions to produce voltages representing high O2 above set point.

Sensors exposed to CO2 following scrubber breakthrough.

Symptoms

Surface

Intermittent "Out of Range" messages on a SINGLE cell (the good one). Failure to calibrate.

Dive

Intermittent "Out of Range" messages on a SINGLE cell (the good one). Failure to calibrate.

Functional Safety Implication

PPO2 controller should withstand multiple cell failures.

Engineer the cells so all failures are in the same direction (low).

Test the sensor ceiling by applying a higher load, while the sensor is in pure O2 during pre-dive checks. For example, if normal load internal to the sensor is 100 Ohms, then apply 50 Ohms to check ceiling is not lower than a PPO2 of 2.0.

10.10 Majority of O2 cells fail during dive

Cause

Fatality occurred where more than two O2 cells failed but system allowed dive.

Diver was partially deaf and did not hear alarms.

O2 sensors were marked with a date code, which was not immediately obvious: all sensors were around 3 years old. Diver was old and may not have recalled change date.

Preventative action

Proper checking of sensors.

Functional Safety Implication

Use sensor fusion algorithm that can detect one good sensor among faulty sensors, and detect any faulty sensors.

Use visual feedback in PFD in addition to audible alarms, or use vibrating mouthpiece.

Pre-dive checks should force the checking of the O2 sensors.

O2 sensors should be marked very clearly in large letters with a date code, such as “SEPT 06”, not “J6” in small letters.

Use different colour sensor bodies for each year.

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Provide means to check sensors automatically when a sensor failure occurs, such as injecting a known quantity of O2. This requires a calibrated O2 injector: this can be done automatically during pre-dive checks.

10.11 O2 Cell Calibration Incorrect

Cause

User error and design omission, allowed the user to calibrate the CCR as if it was 98% O2, when PPO2 level in the loop could have been as low as 48%. Result was Cat III DCI.

Preventative action

All O2 Cells should calibrate in air when the unit is open: users should not be asked to calibrate with a gas supply which may not in itself be calibrated, injecting an uncalibrated amount of gas into an uncalibrated loop volume (the procedure used by the manufacturer).

Functional Safety Implication

Eliminate problem by calibrating on air and check cells are within normal range, and that the cells are likely to be in air (e.g. by sensing exposure to light).

Provide a calibration check interface to enable the diver to check that the calibration has been carried out and the results are correct.

10.12 O2 Cells show different reading to independent PPO2 monitor

Make-Up-Gas flush to check which sensors respond correctly. Bail out. Abandon dive. Unit will maintain O2 limits on the 2 bad cells as they out-vote the good one. O2 will be high.

Preventative action

Replace cells at correct intervals (every 12 months). At start of dive, drive cells above set point to ensure they can respond fully.

Functional Safety Implication

Withstand multiple cell failures.

Engineer the cells so all failures are in the same direction (low) where possible.

10.13 O2 Cells have condensation or vapour on sensor face

Cause

Moist, warm, saturated gas, condensing on objects in the gas flow.

Symptoms

Surface

Normally none.

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Dive

Intermittent "Out of Range" or "Failure" messages on a cell.

Recovery action during Dive

Make-Up-Gas flush to check which sensors respond correctly. Bail out. Abandon dive.

Preventative action

Latest cells have face which is hydrophobic. Insulate loop to lower condensation.

Functional Safety Implication

1. The cells and cell holders shall not allow condensate or vapour to lay on the cell membrane or face.
2. Ensure water can run off the face of the membrane, i.e. it shall not be in a well.
3. Important issue is to ensure calibration is not carried out in cells with water on their faces. This is an issue if the calibration is performed while fitting a new scrubber. The calibration should be performed after the scrubber is closed.
4. The training manual should emphasise the checking of the unit by a Make-Up-Gas flush.
5. Ensure cells have a hydrophobic membrane.
6. Orient cells to avoid water dripping onto cells in normal diver orientations.
7. The O2 Cell fusion algorithm should withstand multiple cell failures.

10.14 O2 Cells have differential pressure applied

Cause

Unequal pressure on front and back of sensor cells during dive.

Symptoms

Surface

None.

Dive

Intermittent "Out of Range" or "Failure" messages on a cell.

Recovery action during Dive

Make-Up-Gas flush to check which sensors respond correctly. Bail out. Abandon dive.

Preventative action

Ensure gas flow to rear of cells. Make sure pressure equalisation holes are clear, and that the sensor pcb has equalisation holes.

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Functional Safety Implication

1. Withstand multiple cell failures.
2. Ensure the design allows adequate gas flow to rear of cells to eliminate the source of failure.
3. Engineer the cells so all failures are in the same direction (low).

10.15 O2 Cell Explodes or Leaks

Cause

Lockout of an O2 Cell in a chamber.

Dropping an O2 cell causing electrolyte leakage

Symptoms

Surface

Shrapnel injury to operator. Strong alkaline spray (KOH).

Dive

Not applicable.

Recovery action during Dive

Not applicable.

Preventative action

Do not decompress O2 Cells faster than a human can withstand.

Functional Safety Implication

1. Verify that sensors specified for product do not produce shrapnel when suddenly decompressed (Torpedo test).
2. Warn operators that if an O2 Cell feels wet, they should wash the sensor and hands in warm water immediately. Requires note in training manual.
3. Verify the O2 sensors to ensure there is no electrolyte leakage if dropped from 1.5m repeatedly and from 3.0m.

10.16 Oscillating sensor

Cause

Peculiar O2 sensor failure mode, where O2 cell value oscillates.

Symptoms

Surface

Not obvious.

Dive

PPO2 is poorly controlled.

Recovery action during Dive

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Switch to manual control.

Preventative action

Well designed electronics should detect this case.

Functional Safety Implication

Very thorough O2 cell screening is required.

10.17 Caustic Burn from leaking electrolyte

Cause

O2 cells contain Lithium Hydroxide as an electrolyte, which has a pH of 14. This is extremely caustic.

Diver handles an O2 cell with leaking electrolyte.

If diver touches his face or eye, the caustic burn may become a serious accident.

Symptoms

Surface

Burning sensation.

Dive

Unlikely.

Recovery action during Dive

Not applicable.

Preventative action

Divers should wash hands after handling O2 sensors.

Functional Safety Implication

Ensure manuals state risk clearly and action to be taken.

10.18 Diver fails to monitor PPO2

See also Section 18.4

Cause

Diver assumes rebreather is managing PPO2, but rebreather has failed.

Symptoms

Surface

Sudden Loss of Consciousness from hypoxia.

Dive

Diver drowns after a sudden Loss of Consciousness.

Recovery action during Dive

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Not applicable.

Preventative action

Electronics should time diver to ensure diver observes PPO2 with required frequency.

Functional Safety Implication

1. Hypoxia risk alarm required, that does not use oxygen sensors: it can compute potential PPO2 deviation from changes in ambient pressure and metabolism. Deviation can be reset to zero when user observes PO2 by forcing user to use switch to see PPO2.
2. This is an equipment issue, not a diver failure, because the diver is human and humans cannot be relied upon to perform every function perfectly all of the time. It is unreasonably hazardous to expect them to do so on a life support system.

10.19 Oxygen cells sensitive to CO2

See also Section 18.4

Cause

Diver shuts breathing loop after dive, with the cells exposed to a few percent of CO2. CO2 reacts with electrolyte in the O2 cells.

Symptoms

Surface

None.

Dive

CNS risk.

Recovery action during Dive

Not applicable.

Preventative action

Cells should be checked for CO2 tolerance.

Functional Safety Implication

O2 cells need to be evaluated for tolerance to CO2.

Fault Study "FS_CO2_exposure_of_oxygen_cells_YYMMDD.pdf" refers, published on www.deeplife.co.uk/or_fmeca.php

11 CARBON DIOXIDE LEVEL FAILURES

11.1 Scrubber Not Fitted

Cause

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User error.

Failure to use checklists.

Difficulty in checking that a scrubber is fitted.

Symptoms

Surface

Rapid breathing, headache. Hypercapnia.

Dive

Stuffiness, rapid breathing, confusion. Hypercapnia.

Recovery action during Dive

Bail out.

Preventative action

Use checklists to ensure a scrubber is fitted on every dive, and is within date.

Implement Functional Safety recommendations.

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Functional Safety Implication

The Functional Safety processes involving this fault mode are complex and extensive. This included:

- Accident Studies (numerous fatal accidents and serious incidents have occurred on rebreathers due to scrubbers being omitted).
- User Focus Groups, to understand the side effects of adding measures to mitigate this risk.
- HAZOPs on the mitigation measures.

The conclusions from these studies are itemised below.

1. It is a Functional Safety requirement for all rebreathers that a means be fitted to enable the diver and supervisor to positively confirm that a scrubber is fitted, without disassembly. This can be achieved using a scrubber viewing port on the scrubber assembly, with a colour contrast: scrubber material is white so a black background should be used. If the scrubber window appears white then a scrubber is fitted, and if black, then no scrubber is fitted.
2. It is within ALARP to fit a device that shuts the breathing loop if no scrubber is fitted. For example, on the Open Revolution rebreathers a spring loaded plate that fits under the flow cone was considered: this closes the gas path by pressing against the flow cone unless it is depressed by the physical presence of the scrubber. There are two factors that led to the Deep Life Design Team not fitting these plates to the Open Revolution rebreathers:
    - User Focus studies found that divers would rely on the plate to confirm a scrubber is fitted, instead of a checklist. The checklist includes the check of the duration of the scrubber (when it was fitted, and the time it has been used). The plate appears to increase the risk of a diver diving a rebreather with an exhausted scrubber.
    - The plate increases the probability of failure, particularly following a caustic cocktail or use in anoxic water where ingress may corrode the stainless steel spring.

    As a result of these considerations, a plate was not fitted. The balance was a fine one in this instance, and alternate conclusions would not be contrary to ALARP.
3. Monitor scrubber health. This is within ALARP on electronic rebreathers, but not otherwise.
4. Monitor scrubber life. This is within ALARP on electronic rebreathers, but not otherwise.
5. Monitor when the scrubber is changed. This again was found to be contrary to the use of checklists, so may have undesirable side effects. It is not implemented in Open Revolution rebreathers as a result.

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6. Monitor PPCO2. This is within ALARP, both for inhaled and exhaled CO2 on electronic rebreathers. The exhaled CO2 monitoring is far safer than monitoring inhaled CO2, as it detects many other fault conditions such as missing or damaged one-way valves in the DSV. The means to monitor exhaled CO2 has been disclosed with reasonable detail.
7. Measure breathing resistance across scrubber, to detect a missing scrubber failure automatically. This is not within ALARP at present, as it involves a complex differential sensor arrangement, which if it fails could result in a CO2 bypass. A further factor is the potential again for the user to rely on this sensor rather than use a checklist.

11.2 Scrubber Physically Damaged, affecting gas X-section

Cause

Poor handling, with poor user check when installing scrubber.

Symptoms

Surface

Rapid breathing, headache. Hypercapnia.

Dive

Stuffiness, rapid breathing, confusion. Hypercapnia.

Recovery action during Dive

Bail out.

Preventative action

Check scrubber visually before installation. If granular scrubber, weigh the scrubber.

Functional Safety Implication

Ensure scrubber seals can tolerate a large degree of scrubber damage.

Provide monitoring of expired CO2 in iCCR and eCCRs/ eSCRs.

Provide scrubber health monitoring in eCCRs.

11.3 Scrubber Exhausted

Cause

Overuse or improper storage. Out of date.

Symptoms

Surface

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Rapid breathing, headache.
Hypercapnia.

Dive

Stuffiness, rapid breathing, confusion.
Hypercapnia.

Recovery action during Dive

Bail out.

Preventative action

Change the scrubber every 3 hours or sooner.

Functional Safety Implication

Monitor scrubber health.

Monitor scrubber life.

Monitor when the scrubber is changed.

Monitor PPCO2.

11.4 Scrubber Bypass

Cause

Gas flows rapidly through a single path in the scrubber and CO2 is not removed.

Bad packing. Material published by APD indicates that a large proportion of their user base cannot pack a granular scrubber properly to prevent this problem.

The most popular axial scrubbers have an endemic by-pass of 0.1 to 0.2% CO2 due to poor scrubber design. This means the scrubber should be tested flat in these designs.

Symptoms

Surface

Rapid breathing, headache.
Hypercapnia.

Dive

Stuffiness, rapid breathing, confusion.
Hypercapnia.

Recovery action during Dive

Bail out

Preventative action

Design-out the problem by using an EAC.

Functional Safety Implication

Monitor scrubber health.

Monitor scrubber life.

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Monitor when the scrubber is changed.

Monitor PPCO2.

Granular material packed by users will not meet Functional Safety at any SIL level.

Design-out the problem using an EAC.

11.5 Excess Work of Breathing

Cause

Diving to excess depth for the rebreather.

Use of filter or skrim material to prevent caustic dust.

Overpacking of scrubber.

Moisture absorbed by scrubber during use increases breathing resistance and hence WOB.

Flooding.

Mushroom valve stuck shut.

Counterlungs change position.

Preventative action

Diver should be trained to be aware of an increase in breathing rate and bail out.

Functional Safety Implication

Measure WOB actively during dive.

11.6 Counterlungs change position, causing CO2 hit

Cause

Possibility to put on rebreather without counterlungs being fixed down.

A fatal accident occurred where the counterlungs floated above the diver due to not being fixed down correctly, causing CO2 retention. This can be due to poor range of sizing or failure to fix down the counterlungs either within the counterlung bag, or fix down the bag itself.

Symptoms

Surface

Not noticeable.

Dive

Increased WOB leading to severe CO2 hit.

Recovery action during Dive

Bail out on to open circuit.

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Preventative action

Service correctly and pre-dive checks.

Diver should be trained to be aware of the importance of fixing down the counterlungs.

Functional Safety Implication

Counterlungs should be fixed down so that user cannot disconnect one end, or fail to attach counterlungs.

Active monitoring of respiratory parameters is needed.

11.7 One Way Valve (Flapper valve) Stuck Open or Partially Open

The term “flapper valve” refers to the whole one-way valve assembly. The assembly comprises a web and a mushroom.

Cause

Valve not fitted.

Valve stuck open due to debris in the valve, particularly following a flood or vomiting into the loop.

Some valve designs allow them to jam open with pulses in the gas stream.

Incorrect assembly: mushroom is inserted on to the wrong side of the web, or the webs are swapped.

The wrong mushroom is inserted.

Web profile incorrect.

Valve form incorrect.

Valve material inappropriate, e.g. EPDM, such that it forms a set over time.

Symptoms

Surface

Same as scrubber breakthrough.

Dive

Same as scrubber breakthrough.

Recovery action during Dive

Bail out.

Preventative action

Pre-dive check for valve operation.

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Functional Safety Implication

1.1.11.1 The function of the two one-way valves fitted either side of the mouthpiece is critical to the safe operation of the unit.

1.1.11.2 The design should be of a type that shall not stick by itself, including material selection and clearances around the mushroom.

1.1.11.3 The flapper valve assembly should be colour-coded so it is obvious to the user which side each valve is fitted to.

1.1.11.4 The web supporting the mushroom should have a means to prevent the mushroom being assembled on to the wrong side of the web.

1.1.11.5 The two webs should be of different size, or keyed, to prevent the inhale valve being inserted in the place of the exhale valve.

1.1.11.6 The valve should preferably be designed to make a soft click sound each time it closes, which the diver can listen to.

1.1.11.7 The web should be tested to ensure the mushroom cannot fold into the web regardless of shock: mechanical or from pulses of gas.

1.1.11.8 The holes in the web needs to be of sufficient size to let small particulate through and not jam. The valve should be assessed for function in the case the diver vomits.

1.1.11.9 The flapper valve and web form should be assessed for the pressure at which it passes gas in the incorrect direction. Whilst the rebreather OPV should avoid differentials of more than 40mbar, the valve should achieve a minimum of 80mbar and ideally 300mbar.

11.8 One Way Valve (Flapper valve) Stuck Shut or Partially Shut

Cause

Valve stuck shut due to sticky material on the valve, particularly following a flood or vomiting into the loop.

Some valve designs are prone to jam shut.

Incorrect assembly: mushroom is inserted onto the wrong side of the web.

The wrong mushroom is inserted to the wrong side of the mouthpiece.

Symptoms

Surface

Diver sees a very high breathing resistance.

Dive

Same as on surface. It should be obvious what has occurred on the surface.

Recovery action during Dive

Bail out.

Preventative action

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Pre-dive check for valve operation.

Functional Safety Implication

Full assessment of one-way valve function is required in mechanical FMECA.

Same requirements as for one-way valve (flapper valve) stuck open or partially open, plus the following:

7. Water should not collect around the flapper valve.
8. The flapper valve should not seal shut if one small area is frozen.

11.9 One-Way Valve missing from one side of the loop

Cause

Design fault allows mouthpiece to be reversed such that the one-way valves face each other: this prevents gas flow around the loop but allows the diver to breathe in and out of one of the counterlungs.

One-way valve fell out, or lost, or not fitted.

The valve on one side of the DSV is reversed.

Symptoms

Surface

No obvious problem unless the diver pre-breathers the loop for 10 minutes or more.

Dive

Hypercapnia.

Recovery action during Dive

Bail out.

Preventative action

Pre-dive check for one-way valve operation is an essential check. Novice divers should not be assumed to be able to carry out this check.

Functional Safety Implication

Compliance with EN 14143 which requires that the mouthpiece is not reversible unless the rebreather operates safely with the reversal.

Webs should be designed such that the diver cannot reverse the valve direction on one-side of the DSV, for example by using mating dimples on the fittings, and ensuring the active side of the valve only is accessible by the diver.

Highlight the need to carry out one-way valve tests before every dive.

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11.10 Caustic cocktail from CO2 scrubber

Cause

Flooding of scrubber.

Water generated by scrubber coming into skin or eye contact.

Symptoms

Burning sensation

Respiratory spasm if inhaled

Surface

Risk of caustic burn from contact with wet scrubber material.

Dive

Risk of respiratory spasm, leading to loss of consciousness.

Recovery action during Dive

Listen for sound of flooding.

Bail out.

Divers should avoid skin contact with scrubber material

Preventative action

Use EACs which have greatly reduced caustic risk.

Positive and negative pressure checks prior to dive.

Functional Safety Implication

1.1.11.10 The rebreather should be highly resistant to flooding, using double seals where reasonable possible, and ensuring all fittings are very secure.

1.1.11.11 Use EACs to minimse risk of caustic cocktail.

1.1.11.12 User manuals should explain caustic risk and avoid diver having liquid from scrubber touch his lips, face, or tongue.

1.1.11.13 Provide water traps in mouthpiece as well as in counterlungs to prevent liquid touching the diver's lips, or by inhalation.

1.1.11.14 Provide electronic flood warnings where within ALARP to do so.

1.1.11.15 Provide audible warning of flood (structures that create a clear gurgling sound when a flood starts).

11.11 Hoses pinched or kinked

Cause

Unsuitable hose design allows kink, preventing gas being supplied, or causing WOB to increase.

Preventative action

No hose should not kink or pinch when bent back on itself.

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Functional Safety Implication

End-to-end scope with respect to hoses covered by a requirement in EN14143:2003. Hoses should not kink or pinch.

11.12 Loop Flow Direction Swapped Accidentally

Cause

One-way valves swapped.

Connectors swapped.

Preventative action

It should not be possible to swap the loop flow direction accidentally.

Functional Safety Implication

1.1.11.16 One-way valve assemblies shall be designed so it is impossible to insert the mushrooms from the wrong side of the web.

1.1.11.17 One-way valve assembles shall be designed so it is impossible to swap webs from inhale to exhale.

1.1.11.18 Connectors and hose lengths shall be designed so it is not possible to swap the hoses accidentally, from inhale to exhale.

1.1.11.19 Effect of reversed flow shall be assessed.

11.13 Premature Counterlung Failure

Cause

Use of inappropriate materials that degrade in sunlight or in salt water.

Poor welding.

Poor abrasion resistance.

Poor puncture resistance.

Preventative action

Use correct materials.

Functional Safety Implication

Verify the material performance under a wider range of conditions.

11.14 Counterlung blocks ports

Cause

On negative pressures, the counterlung material folds over any of the ports, blocking it. This increases the breathing resistance considerably, and may prevent the ALV from working.

Preventative action

Fit a spring or coil in the counterlung, and ensure that sufficient coils are captured by each of the ports to prevent a large reduction of breathing loop cross section from occurring.

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Functional Safety Implication

Verify the WOB does not increase suddenly with negative loop pressures.

11.15 Structures that bypass the scrubber

Cause

One contemporary rebreather was found to have a water drain valve that runs across the scrubber, opens under specific conditions of loop volume and pressure, allowing breathing gas to bypassing the scrubber.

The rebreather also had oxygen sensors across the scrubber: if a sensor falls out, then again the scrubber is bypassed.

Preventative action

Avoided by applying proper safety design processes.

Functional Safety Implication

Do not use any structure that can bypass the scrubber under any circumstances.

Verify the loop operates correctly under all plausible fault conditions and pressures using formal methods.

11.16 Very low diver tidal volume

Cause

Incapacity of the diver ((unconscious or nearly so).

Poor respiratory habits.

Symptoms:

Diver will likely exhibit symptoms of hypercapnia because gas exchange will be poor, so will have very rapid breathing.

Preventative action

During diver training, ensure diver breaths normally from the rebreather.

Functional Safety Implication

Where the diver is incapacitated when breathing from a rebreather loop, the balance of probabilities based on accident data and HAZOPs is that the rebreather loop is likely to be contributory. The rebreather should therefore bail out the diver onto a known good gas. The WOB of that alternative source is not a factor, provided that WOB implements ALARP principles.

Monitor the diver's respiratory rate. Where the rate falls outside safe limits, provide a warning and an alarm. Appropriate limits appear to be 20 to 25 bpm for a warning, and 25 to 30 bpm for an alarm: with hypercapnia that is a feature of this fault, the diver's respiratory rate will increase significantly. In this event, an alarm should bail out the

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diver onto a safe gas, as in the balance of probabilities based on accident studies is that the diver's low respiration is caused by the rebreather loop. Thermal sensing is a low cost method of implementing a respiratory rate sensor, so this issue is within ALARP to resolve.

Where possible monitor tidal volumes. This may or may not be within ALARP.

11.17 Sensory system false alarm

Cause

Sensor failure.

Electrical noise.

Program error.

Tradeoff in alarm matrix between false alarms and detecting hazard combinations.

Symptoms:

Warning or alarm is triggered inappropriately.

Preventative action

Diver should act as if the alarm is correct.

Advanced divers or supervisors may fault track to check alarm with special training, but dive action should be as if alarm is correct until proven otherwise.

Functional Safety Implication

Electronics and software should comply to EN 61508 to eliminate program faults.

Other sources are not entirely avoidable: detecting hazards in combination will generally require a false alarm rate that is not zero.

12 FLOODING AND DROWNING

12.1 Loop Flood

Cause

1. Puncture or structural failure in the loop.
2. Hoses from EPDM do not split, but develop small holes.
3. Hoses can separate from their couplings.
4. Counterlung could fail catastrophically due to seam failure.
5. Sharp edge causes wear on Counterlung.
6. Connectors may not be installed correctly.

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7. Connectors have inadequate keying, particularly where these penetrate the scrubber canister or counterlungs.
8. OPV diaphragm damaged, deformed or foreign material under diaphragm.
9. Mouthpiece is lost from diver's mouth, including due to LOC or disability (hypoxia, hyperoxia, hypercapnia, trauma, or other medical condition).
10. Some types of hose clamp, e.g. cable ties, do not apply pressure underneath the locking mechanism in the tie, allowing water ingress into the hose.
11. Flooding results in a loss of buoyancy. Fatal accidents have occurred where the diver cannot achieve positive buoyancy after a flood.
12. Failure to carry out positive and negative pressure checks prior to diving.
13. OPV lets water into the loop when it operates.

Symptoms

Surface

Pre-dive check failure. Unable to hold set point.

Dive

Gurgling and other signs of water in loop. Breathing resistance.

Loss of mouthpiece.

Recovery action dur

Preventative action

Perform positive and negative pressure checks

Minimise risk by good design.

Fit mouthpiece retainer.

Close the breathing loop when mouthpiece is out of the diver's mouth.

Protect hoses with covers and service regularly. Pre-dive checks.

Ensure buoyancy device can float the diver with a fully flooded rebreather.

Functional Safety Implication

12. Fit a mouthpiece retainer (gag strap) as standard.
13. Shut the breathing loop automatically if the mouthpiece is not in the diver's mouth.
14. Fit a buoyancy device to SCUBA rebreathers (i.e. not umbilical rebreathers), with enough lift for the diver with worst case equipment configuration and a flooded rebreather. This appears to be 22.5kg for

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general diving, and 40kg for trimix or heliox diving (due to the extra weight of stage bottles). Fatal accidents have occurred where insufficient lift has been implicated.

15. Monitor moisture and WOB if within ALARP to do so. Warn user of flood and give instructions to bail out.
16. Design-out risk of connectors not being installed correctly by using very positive identification and colouring to show how far the connector should be installed.
17. Ensure Counterlung can withstand shock pressures of 500mbar (e.g. 25 cycles of 1 minute during manufacture, as is applied to buoyancy devices manufactured to meet EN 1809, with all 100% production testing).
18. Hoses should be made from EPDM not silicone or easily pierced materials. It may be better not to have a wrap over the hoses, so damage is more immediately apparent. Survey of hose leakage on Rebreather World confirms hoses of thick EPDM construction fail with small leaks before any major leak occurs. This is not true of thin-walled hoses.
19. Eliminate all failure points into scrubber by providing full hose connector as an integral part of the scrubber canister, rather than using keyed or bonded elements.
20. Ensure OPV diaphragm does not fold, and is tear resistant.
21. Ensure ALV diaphragm does not fold, and is tear resistant.
22. Counterlung fittings require a welded retainer ring to prevent them pulling out of the counterlung.
23. Seals around scrubber shall stand over-pressure and under-pressure. In general, a one bar over pressure and one bar under pressure test should be used for the entire rebreather loop as a design integrity check, and check there is no flood under these conditions.
24. Seals need to be appropriate: lip seals should be used for protected moving surfaces due to their ability to adapt to a wider range of tolerances than O-rings, but lip seals are more delicate so need to be assessed individually.
25. Avoid double layer Counterlungs, as damage is not visible and it may pass a positive pressure test when there is in fact a leak.
26. Connectors need to be secure and not detach accidentally.
27. Connectors need to minimise the leak risk by using double seals where within ALARP.
28. Ensure OPV does not let water into the breathing loop when opening frequently.
29. Cable ties should be avoided in any situation where a cable tie without the bridge underneath it would allow a leak, as users may replace cable ties in the field without realising the importance of the bridge in the factory installed tie. Where possible, avoid cable ties, using Jubilee claps or similar.

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30. Pull dumps on counterlungs or within the breathing loop should be fitted with one way valves to limit water ingress.
31. Mitigate against the effect of a flood by:

    1.1.31.1 Ensuring the scrubber does not produce a caustic cocktail with a short duration flood.

    1.1.31.2 Fit snorkel tubes to prevent water running directly into the diver's DSV.

    1.1.31.3 Fit water dumps to allow water to be emptied from the rebreather.

12.2 Mouthpiece floods rebreather

Cause

Mouthpiece cannot be shut (either diver has a disabling injury, or it fails mechanically).

Symptoms

Surface

None.

Dive

Rebreather floods through mouthpiece.

Recovery action during Dive

Mechanical failure: diver needs to stay on the loop.

If diver has a disabling injury, if the BC does not have enough lift, then this is a very serious failure. Buddy needs to dump stage cylinders, and if this is not enough, dump weights.

Preventative action

Avoid by design.

Ensure mouthpiece retainer (gag strap) is fitted and used.

Auto-shut-off the mouthpiece if it is out of the diver's mouth to prevent a flood.

Functional Safety Implication

32. Ensure the BC is big enough to lift a flooded rebreather
33. Fit a mouthpiece retainer
34. Design the mouthpiece to shut off automatically if out of the diver's mouth.

12.3 Mouthpiece failure (i.e. failure to allow diver to breathe from loop when this is desirable)

Cause

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Mouthpiece bite not well attached to mouthpiece.

No mouthpiece retainer and diver has LOC or disabling injury.

Connector failure.

Symptoms

Surface

Mouthpiece comes away.

Dive

Diver cannot breathe from loop.

Recovery action during Dive

Use a secondary regulator (Octopus regulator).

Preventative action

Avoid by design, that connectors, hoses and mouthpiece do not fail if the diver snags them on the dive boat or underwater.

Ensure mouthpiece retainer (gag strap) is fitted and used.

Functional Safety Implication

1.1.34.1 Ensure the mouthpiece can withstand the weight of a diver (100kg for 1 minute).

1.1.34.2 Ensure all hoses and connectors can withstand the weight of a diver (100kg for 1 minute)

1.1.34.3 Fit a mouthpiece retainer as standard.

12.4 Counterlung ports pull out from counterlung

Cause

Failure to reinforce the port cutouts in the counterlung, and key the port cutout, such that the CL can pull out from the port.

Preventative action

Ensure port reinforcing rings are fitted with strong positive keying.

If a two layer counterlung is used, ensure inner layer is larger than outer layer.

Functional Safety Implication

Ensure ports and counterlungs withstand a 100kg pull: the largest plausible force that will be applied, and also withstands at least a 300mbar overpressure under these circumstances.

Fit a reinforcing ring to the counterlung that positively latches the port mouldings.

12.5 Implosion or explosion on compression or decompression

Cause

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If rebreather is not being breathed from, and either compressed or decompressed, an implosive or explosive could compromise a seal or damage a part, such as in medical chamber interlocks or diving with the diver not breathing from the breathing loop.

Preventative action

Avoid by appropriate design.

Functional Safety Implication

1.1.34.4 Ensure rebreather can withstand underpressure or overpressure by one bar.

1.1.34.5 Ensure rebreather can withstand a total pressure of double the maximum diving depth.

1.1.34.6 Assess the effect of compressing a rebreather with all ports closed and gas off, to the maximum diving depth, in a chamber (i.e. out of the water, where implosion or explosion effects will be more severe).

1.1.34.7 Perform the same assessment for the rebreather after saturating in helium gas at the maximum diving depth, then decompressing.

1.1.34.8 OPV needs to vent at a sufficient rate for the worst case ascent, to keep the rebreather within the tested maximum loop over-pressure.

12.6 Counterlung or hose pinched

Cause

On commercial diving rebreathers, the stab plate to the helmet can pinch a counterlung into a port if it they are protected.

On other rebreathers fixings can pinch counterlungs.

Preventative action

Avoid by appropriate design.

Hoses should be highly resistant to pinching.

Hoses should be able to be bent 180 degrees without kinking.

Functional Safety Implication

35. Ensure nothing can pinch the counterlung during assembly.
36. Emphasise the need to carry out pre-dive checks.
37. All breathing hoses shall be able to be bent 180 degrees in their minimum possible radius, without kinking.
38. All breathing hoses shall withstand at least 10kg pressure applied over a 100m length without the internal diameter being shut off.

12.7 Counterlung or rebreather component pierced

Cause

Packing sharp objects on counterlungs.

Physical abuse.

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Customs or security or policing, by use of sharp probes to piece equipment in order to obtain a gas sample.

Preventative action

Avoid by appropriate design, handling and pre-dive checks.

Functional Safety Implication

39. Divers should not pack items on or in the counterlungs.
40. Emphasise the need to carry out pre-dive checks including visual inspection.
41. Shipping label should state clearly that security inspections shall not use sharp probes to sample the gas.

12.8 Lack of water drain

Cause

For technical rebreathers, a means to remove water from the breathing loop is required as the risk of flooding in a situation that could escalate is significant.

Preventative action

Design in.

Functional Safety Implication

Rebreather should be fitted with a safe means to drain water, during the dive.

12.9 Water Drain Failure

Cause

Either mechanical failure, or particularly, failure to realign the sealing pad after use.

Sealing pads may more sideways, preventing them sealing: some pull dumps do this much more often than others.

Preventative action

Design in.

Functional Safety Implication

One way valves shall be fitted to water dumps on the rebreather loop to prevent excessive water ingress.

The water dump should be optimised to the extent possible within ALARP to ensure the sealing pad reseats correctly after use.

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13 OTHER REBREATHER EQUIPMENT FAILURES

13.1 Pressure causing implosion

Cause

Gas cavities in the equipment.

Use of inappropriate materials, or materials of insufficient strength.

Operating equipment beyond the design limits.

Loss of silicone oil in oil compensated chambers.

Symptoms

Surface

Not applicable.

Dive

Sudden loss of function.

Loud explosion.

Recovery action during Dive

Bail out

Preventative action

Competent design and operation.

Functional Safety Implication

Ensure equipment is designed and verified to operate to at least twice the maximum operating depth any user can use the equipment.

It is hazardous to set any depth limit except that imposed by human physiology. That is, if a manufacturer sets a 100m limit, some users will take the equipment to 200m, or if 200m is set, some users are already taking those rebreathers to beyond 300m.

The human physiology depth limit is 701msw without GABA blockers. The deepest dive to date has been to 701msw, in Comex chamber dive trials.

Based on this reasoning, to verify the equipment does not implode, the test systems should be designed to subject the equipment to twice that pressure, namely 1402msw for commercial rebreathers and at least 400msw for SCUBA rebreathers, preferably 600msw.

13.2 Rebreather BC Failure

Cause

Puncture or structural failure of BC.

Substitution by a BC not designed for the equipment.

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Unsuitable BC, trapping hoses etc.

Symptoms

Surface

Unable to inflate.

Inflation of unsuitable BC impairs use of the rebreather, such as by moving the breathing hoses.

Dive

As per surface and unable to maintain buoyancy.

Recovery action during Dive

Abandon dive. Use alternative buoyancy source. Ditch weight belt if necessary.

Preventative action

Service regularly and test/inspect.

Design and test BC to EN1809.

Functional Safety Implication

Outside eCCR, but covered in "end to end" clause.

Sell BC with rebreather, where a BC will be used.

13.3 Harness Failure

Cause

Structural failure of component.

Symptoms

Surface

Back unit swings and becomes loose.

Dive

Unlikely as unit's weight is water-supported.

Recovery action during Dive

Tighten other straps. Abandon dive if unable to re-secure.

Preventative action

Service regularly and test/inspect.

Functional Safety Implication

Use multiple attachment points.

13.4 Pressure Sensor Failure.

Cause

Any pressure sensor failure (gas contents, ambient, differential).

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Recovery action during Dive

Abort dive.

Preventative action

Monitor pressure monitors frequently.

Functional Safety Implication

The failure modes of the pressure sensors should be determined, and failure actively detected. The appropriate warning can then be raised.

Ambient pressure sensor failures can cause critical errors in oxygen sensor calibration processes, where the pressure sensor is used to determine ambient pressure. It is essential that the user be prompted to check the ambient pressure is the same as the indicated pressure when sensors are used for this purpose, and to use appropriate limits to the sensor values.

Ambient pressure sensor failures can result in a critical increase in decompression risks: redundant sensors would mitigate this.

Cylinder contents pressure sensor failure can result in the loss of gas during a dive.

13.5 Noxious chemical off-gassing

Hazard

Many materials off-gas toxic chemicals when decompressed, at levels far above the permitted occupational exposure limits.

Sports Instructor (G. Stanton, Wakulla Dive Centre), has reported lung burns from a month using a rebreather making extensive use of Delrin and POM.

Note that offgasing in a dive environment is different to outgasing in vacuum: the helium content of breathing gas appears to purge gas from the volume of the plastic, and the high PPO2 causes an accelerated ageing of the plastic. Moreover, many plastics used in vacuum applications absorb water, or are too brittle, for use in marine applications.

The US Navy prohibits Delrin and POM for rebreather applications.

Cause

Unsuitable materials in breathing loop.

Contamination of breathing loop.

Preventative action

Check all plastic materials and coatings used in breathing loop for health hazards, by appropriate searches and MSDS checks.

Functional Safety Implication

Checks of plastics used in rebreathers identified a broad spectrum of toxic chemicals used as plasticisers or softeners, or are residual products from the manufacturing process.

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The plastics listed below as acceptable were chosen after extensive consultation, and an exhaustive review of the Polymer Data Handbook listing over 200 commercially available polymers [13].

In reviewing MSDS data, NASA data on "Outgassing Data for Selecting Spacecraft Materials" [11], and information from vacuum plastics suppliers, including Boedeker Plastics [12]. Samples of the plastics chosen were tested by Deep Life using a mass spectrometer to analyse gas from the plastic samples after pressurisation in Heliox. The following conclusions are made:

- The number of different plastics used should be kept to the minimum.
- The following materials should be banned from use in breathing loops for the reasons noted below:
    a. **PVC** and partially reacted polymers should not be used due to their continuous off-gassing of highly toxic substances.
    b. **Polyoxymethylene (POM),** also known as **Acetal, Polyacetal** and **Polyformaldehyde** is sold under tradenames such as Delrin and Histaform. POM should not be used in any significant quantity or at all in the breathing loop. This restriction applies to all similar Acetyl plastics due to its decomposition and heavy contamination when new, offgasing formaldehydes. POM oxidises in chlorine, including by exposure to the chlorine in training pools, resulting in further offgasing and causing stress fractures. The lung burn reported above was due to Delrin and POM offgasing.
    c. **Polycarbonate**, including Lexan, normally contains Bisphenol A as a key building block: this offgases in a diving environment, and exposes the diver to this carcinogen. Polycarbonate free of Bisphenol A is available, but is uncommon.
    A second problem with polycarbonate is that it is weakened by exposure to strong bases, as may be present in a rebreather after a flood.
    d. **Polybutyleneterephthalate (PBT)** has an UL94 V-0 rating, low offgasing and low water absorption. PBT can fail suddenly after exposure to strong bases as may be present in a rebreather.
    e. **Aromatic Polyurethane** contains aromatic isocyanates: isocyanates are known skin and respiratory sensitizers. Aromatic urethane turns yellow under exposure to UV light to release further isocyanates, and can lose mechanical properties long term.
    f. **Neoprene** has offgasing hazards.
    g. **Cordura and nylons** have leak and resilience hazards when used for counterlungs (increasing WOB). Black

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polyether TPU free from softeners appears to be the optimal counterlung material (see next section).

h. **Butyl rubber, Natural Rubbers** and **Latex** invokes an allergic reaction in a significant proportion of the population, so should not be used in rebreathers. See Section 18.5

- **The following materials are generally acceptable in breathing loops, subject to the notes below:**
  a. **Kynar** is preferred for hard plastic parts: it is the purest of all the synthetic resins, is a tough plastic with low water absorption but is heavy and applying ALARP it was found it could not be moulded into many of the desired forms for rebreathers reliably – Kynar has a high shrinkage (around 4% linear), leading to voids and dimensional non-conformance in mouldings. It is suitable for use in rebreather oxygen lines where a plastic is required.
  b. **Polypropylene (PP)** without any plasticiser or softener is an acceptable alternative to Kynar. Shrinkage is high at around 2.4% (linear). PP has a resin identification code 5 + PP, for recycling.
  c. **Acrylonitrile Styrene Acrylate** (**ASA)** with special efforts to purge it of unreacted chemicals and contaminants is acceptable as an alternative to PP where PP shrinkage makes the material unacceptable. Some grades offgas formaldehyde: the ASA source shall be strictly controlled to ensure the Acrylonitrile is fully reacted.
  d. **PEEK** and **PTFE** are the only approved high pressure valve seats material for oxygen service, but the mass shall be kept to the minimum required. PEEK is preferred because PTFE is a very weak material with poor wear properties. PTFE has a resin identification code 7 + O: PTFE, for recycling, PEEK is identification code 7.
  e. **Polyether Polyurethanes**: Fully reacted Thermoplastic PUs formed from aliphatic polyether polyols are acceptable for components that need to be strong and flexible, but the TPU needs to be black as otherwise it degrades under long term exposure to UV light. Vulcanising PU (PUR) shall not be used unless it is confirmed it is an aliphatic polyurethane and is fully reacted. Thermal decomposition products of aliphatic polyether polyols include carbon monoxide, oxides of nitrogen, and hydrogen cyanide, so the TPU may not be used anywhere adiabatic compression is a hazard or in any application where the TPU may be overheated. RF welding temperatures shall be tightly controlled. TPU

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has a resin identification code 7 + O: TPU, for recycling. Polyester polyols are suitable for use in marine applications due to their accelerated breakdown in chlorinated water: only polyether polyols are approved.

f. **EPDM** normally contains Thiram, but can be supplied without it, and is the preferred material for breathing hoses and O-rings that are dynamic or come into contact with medium pressure oxygen or strong bases. EPDM has a resin identification code 7 + O: EPDM, for recycling.

g. **Silicone rubber** should be injection moulded, and not formed using room temperature silicone in solvents. Silicone is acceptable for seals that are not in contact with high pressure oxygen. Silicone oil and lubricants containing silicone oil shall be kept away from silicone seals. Silicone has a resin identification code 7 + O: Si, for recycling.

h. **Viton O-rings** are the only O-rings suitable for high pressure oxygen.

- All **lubricants** require an auto-ignition pressure to be tested in pure oxygen and that pressure should be at least 50% higher than their maximum service pressure. Tribolube 71 LP and Tribolube 71 HP are recommended.

13.6 Entrapment Hazard

Cause

Hooks and features that give rise to an unreasonable risk of dive entrapment.

Attachment of rebreather to the diver by secondary points.

Symptoms

Surface

Snagging on dive benches etc.

Dive

Line entrapment.

Fatal accidents have occurred where divers have used other straps, then removed rebreather in the water, to find the rebreather sinks, pulling them down.

Recovery action during Dive

Avoid lines, and move slowly when entrapped, cutting away line.

Preventative action

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Diver should carry at least two blunt ended line cutters: for example a pair of surgical shears and a covered razor line cutter, accessible to either hand.

Avoid by design.

Jubilee clips should be covered. Shackles should be selected for low entrapment risk.

Note it is impossible to eliminate entirely, except with a naked diver, however even naked fish manage to get entrapped in nets!

Functional Safety Implication

Every part of the rebreather should be reviewed to determine the line entrapment hazards.

Avoid hooks and lines that increase the entrapment risk significantly.

Hoods should be used on all Jubilee clips.

Divers should be trained not to fix the rebreather to their body except using the harness that came with the rebreather.

13.7 BOV or DSV Guillotines Diver's Tongue

Cause

BOV or DSV where the shut off action moves a blade or edge across the mouthpiece. If diver's tongue is in that space, then it can be guillotined. This is particularly important in automatic shut-off valves, but has occurred on a manual DSV.

Symptoms

Surface

Diver's tongue is either caught in the DSV or BOV, or a section of the end of his tongue is cut off.

Dive

As surface, but likely to escalate into a serious dive accident.

Recovery action during Dive

Do not put body parts into the DSV or BOV.

Preventative action

Avoid by design. DSVs with spring powered action, and BOVs in particular, should orient the moving barrel to rotate around the mouthpiece rather than cross the mouthpiece.

Functional Safety Implication

Barrel of DSVs, BOVs and ALVBOVs should rotate in the axis of the tongue, not across it, to eliminate any possibility of this fault.

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13.8 Infective Bacteria, Fungi, Yeasts and Viruses

Cause

Failure to clean diving equipment, particular counterlungs and wings.

Fungi infection risks include Aspergillus fumigatus (see below).

Bacterial risk infections include TB.

Yeasts include Canditis.

Virus infection risks are likely to be extensive.

Symptoms

See the tragic case of Mike Firth on www.divernet.com/other_diving_topics/medical_health/682407/think_twice_before_breathing_off_a_bag.html and then www.diveoz.com.au/discussion_forums/topic.asp?TOPIC_ID=24651, both with capture dates of 13th February 2011

Two breaths from a wing, resulted in Mike Firth losing 70% of his lungs from Aspergillus fumigatus fungi infection, requiring oxygen continuously. To quote Mike before he died "It's like having your face blown away and it makes my mouth and nose tissues very sore … having to settle for being able to walk no more than about 15 metres, and my buddy is a long line with piped O2."

Recovery action during Dive

Not applicable.

Preventative action

See UK HSE Information Sheet 12, Cleaning of Diving Equipment, www.hse.gov.uk/pubs/dvis12.pdf.

Clean all wings, rebreather counterlungs and respiratory components in clean water after every dive, and at least once a week (preferably daily), clean using Virkon solution.

Functional Safety Implication

Ensure all rebreather and wing user manuals contain instructions on cleaning the rebreather.

Ensure all training courses include instructions on cleaning the rebreather and the effect of not cleaning.

Publish the accident above in the rebreather list, as diver was rebreathing from a wing, to make divers aware of the critical importance of cleaning counterlungs and wings.

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13.9 Insects inside loop

Cause

Open ports into a rebreather, seem to attract insects. During Deep Life test diving, there were several incidents where insects were found inside the breathing loop before or, worse, immediately after a dive: a cockroach, ants, and the spider below – identified as female Redback spider (*Latrodectus hasselti*), considered one of the most dangerous spiders in Australia.

Symptoms

Surface

Surprise for the diver. A bite from a venomous spider on the tongue, such as the Redback or the related Black Widow, can be lethal.

Dive

Unpleasant surprise, which may escalate to panic with divers with phobias. Possible serious injury to the diver from bites to the mouth or tongue. Venomous insects may cause swelling of the tongue and a respiratory collapse, or other reaction to the toxins.

Recovery action during Dive

Bail out, take mouthpiece out of mouth and flood it, then hit the purge button, then turn to the breathing loop carefully.

Preventative action

Cap off all ports when not in use.

Wash rebreathers thoroughly after periods in storage.

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Functional Safety Implication

Caps need to be available for ports commonly disconnected by the user.

13.10 Argon Narcosis from using less than 99% pure Oxygen

Cause

Use of oxygen less than 99% pure in a CCR results in the rebreather filling gradually with argon.

Argon is 2.3 times more narcotic than nitrogen, and the form of the narcosis is reported to be more disabling.

Almost all the impurity in oxygen is argon. As the oxygen is metabolized, the rebreather gradually becomes full of argon.

For example a cylinder with 95.5% oxygen will contain around 4.5% of argon, because when the nitrogen is removed from air, the 20.9% Oxygen becomes 4.7 times enriched and so is the argon.

Oxygen is produced by three main processes. For a summary of the separation processes, see Air Products, A review of air separation technologies [10].

The main processes for producing oxygen are cryogenic distillation, membrane separation and molecular sieves.

In cryogenic separation the boiling points of the various gases are:

- Oxygen has a boiling point of -183.0 °C
- Argon has a boiling point of -185.85 °C
- Nitrogen has a boiling point of -195.76 °C

Hence the cryogenic separator removes nitrogen easily, but the separation of argon from oxygen requires extremely tight control, or frequently, use of a separate process. For non-diving grade oxygen, e.g. welding oxygen, there is no benefit from this extra cost, so the argon is left in the gas.

Membrane separation and molecular filters produce the same result, because nitrogen is absorbed much more readily than oxygen and argon.

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The argon in oxygen in a rebreather does not act like a make-up-gas (a.k.a. diluent), because it is added continuously through the dive. It gradually displaces the intended make-up-gas with argon.

This is a risk in CCRs of all types: it is not a significant risk in SCRs because the EAN of the main gas will contain enough nitrogen to enable the breathing loop to vent regularly.

Symptoms

Narcosis at shallow depth: argon is 2.3 times more narcotic than nitrogen at any given depth.

"LSD" like hallucinations: argon narcosis is reported to be not the same as nitrogen narcosis.

Recovery action during Dive

Bail out.

Preventative action

Use only pure oxygen (with at least 99% oxygen) on the oxygen side of CCRs.

Functional Safety Implication

Ensure this information is in the training manuals and user manual.

14 ASSOCIATED EQUIPMENT FAILURES

The associated equipment is equipment used in conjunction with a rebreather, but that does not form part of the rebreather or its monitoring.

14.1 Gross dry suit leak

Cause

Poor maintenance.

Zipper failure.

Ripped suit material.

Dry suit over-pressure-valve is single mushroom type and the mushroom catches on the web supporting it.

Use of dry gloves and the dry gloves are punctured.

Preventative action

Check dry suit carefully before use.

Handle zippers carefully.

Use proper maintenance and inspection.

Use double valve OPVs on dry suits.

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Functional Safety Implication

Covered by “end to end” clause.

Use of dry gloves that allow the entire suit to flood are unsuitable for decompression diving without active suit heating or good surface support (e.g. a diving bell).

Provide active suit heating using self-regulating carbon monomers to maintain the thermal balance for 30 minutes (max time for diver to return to bell).

14.2 Entrapment Hazard

Cause

Hooks and features that give rise to an unreasonable risk of dive entrapment.

Fins, accessories, tanks, valves may all become entrapment hazards.

Symptoms

Surface

Snagging on dive benches etc.

Dive

Line entrapment.

Recovery action during Dive

Avoid lines, and move slowly when entrapped, cutting away line.

Preventative action

Avoid by design. Note it is impossible to eliminate entirely, except with a naked diver, however even naked fish manage to get entrapped in nets!

Functional Safety Implication

Avoid hooks and lines that increase the entrapment risk significantly.

14.3 Polarised or Filter Mask Prevents Reading of LCD displays

Cause

Polarised masks of some types prevent LCDs being read, because LCDs rely on a polarisation to display data.

Some UV filter masks have the same effect.

Symptoms

Surface

Unable to see dive computer or rebreather controller.

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Dive

Ditto.

Recovery action during Dive

Switch to a plain mask.

Preventative action

All polarised masks should be checked against the LCD displays on the dive computer and the rebreather controller on the surface, prior to the dive.

Functional Safety Implication

Highlight risk to the diver of using untested polarised masks.

Provide an OLED or LED display backup for the HUD or PFD.

15 DECOMPRESSION COMPUTER FAILURES

Deco risks are inherent to rebreather use, therefore in accord with Functional Safety that safety monitors shall monitor all risks, deco need to be managed by an electronic rebreather controller or an electronic rebreather monitor.

Review using same fault list as for rebreather controller.

Dive computers have been obtained, exhibiting the following faults:

1. Hanging.
2. Reset underwater, with restart not apparent to diver, with reset of decompression obligations.
3. Failure to warn of narcosis risk when it exceeds that of air due to lower PPO2
4. Failure to computer deco correctly when PPO2 in loop is lower than that of air at the same depth.
5. Incorrect implementation of decompression algorithms. Note, even the example in the original Buhlmann paper has bugs (considers only 13 tissue compartments instead of 16).
6. Failure to manage bail out gases correctly, causing a reduction in deco time.
7. Miscellaneous bugs that cause incorrect decompression computation with particular gas combinations, or in excess of a particular depth.
8. Displays that are not clear, not readable in dark conditions, or are too small.
9. Failure to monitor the actual helium content of the gas in heliox or trimix dives.

All dive computers that have been examined in this study comprise a single unverified processor. None appear to be running code that is capable of formal verification due to language or construction.

Functional Safety Implications

1. Dive computers used by the diver are very unlikely to meet Functional Safety requirements. The rebreather should therefore provide warnings and alarms if decompression obligations are being broken, in addition to the dive computer: these warnings and alarms do not substitute for a dive computer.

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2. PPO2 and Helium measurement is required to compute the decompression obligation correctly. Accuracy of PPO2 measurement is in the region of +/- 0.1 atm, and helium is +/-20%, for alarm purposes though ALARP should be applied.
3. Decompression algorithm should be formally modelled and then verified to functional safety standards.

16 FAILURES SPECIFIC TO DIVES IN COLD WATER

16.1 Effect of cold on the rebreather

The exothermic heating from the scrubber may suggest that a rebreather is a suitable tool for diving in cold water. This is not the case. Rebreathers are fundamentally unsuitable for very cold water, particularly water below freezing, unless the rebreather is designed specifically for that purpose and incorporates sufficient safe heating elements to keep the equipment warm and free of ice: this requires heating to around 20C due to the speed at which ice can form on barriers such as the breathing hoses, or around objects where the gas flow is the fastest, such as mushroom valves and gas injectors.

Diving in water below 4C, poses special hazards. The risks increase with reducing temperature, as shown below.

Temperature	Risk
Above 4C	Low risk
Below 4C	Significant risk of death
Below 0C	High risk of death
Below -4C	Almost certain death

The risks occur from the following causes:

1. The moisture in the breathing loop is almost pure water, so freezes at a higher temperature than sea water. The water can freeze in the breathing hoses, on the mushroom valve, or in the scrubber.
2. The oxygen sensors do not perform correctly at very low temperatures. This will lead to large errors in PPO2.
3. The scrubber efficiency drops as the square of the temperature. At around ir just below zero, granular scrubbers can stop working.
4. The expansion of injected gas in the humid environment of the rebreather will cause ice to form on the injector nozzle. This can block the injector, so the injector is heard to fire (click) by the user (if a solenoid design), but is not injecting gas.
5. “Dive reflex” causes a large increase in blood pressure when the head is in cold water.
6. Risk of shock on entering very cold water, with inhale auto-response.
7. Risk of dry suit leaks are much more serious in very cold water.

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8. Risk of mechanical damage due to ice forming and expanding during equipment storage.
9. Risk of over contraction of silicone oil used to equalise pressure at depths rupturing electronic housings.
10. Risk of inappropriate materials cracking with mechanical shock in a cold environment.
11. LCD displays lose contrast in very cold conditions. OLED displays are strongly preferred.
12. Some integrated circuits, particularly Flash memories and DRAM, do not function well in cold conditions. This can cause corruption of the controller program and data.
13. Batteries will go flat much faster in cold conditions than in warm, and their internal resistance rises even when fully charged. This creates more power supply noise, and will cause equipment malfunction if there is any under performance in the power regulators. Sudden power loss can occur with some battery types.

Functional Safety Implications

For diving in very cold water, it is necessary to have a SIL rated heating system in the counterlungs, sufficient to keep the loop temperature above 20C, and to have active monitoring of the gas flow so that any blockage can be detected.

Equipment should be stored in a warm location, and at all times when not in the warm location, the equipment should be operating to maintain its temperature.

EN14143:2003 requires the equipment to be tested with storage to minus 30C, for material suitability. Some dives are in environments colder than this, such as in Russia in winter and polar dive expeditions. The equipment is wet when it comes out of the water, so chill factors become an issue also, reducing the effective temperature of the surface of the equipment.

16.2 Thermal respiratory shock

Cause

Gas in dive cylinder is cooled by 30C by expansion from first stage, which can result in cold gas being inhaled when the ambient temperature is below 7C. See B. Morgan, P. Ryan, T. Schultz and M. Ward, “Solving Cold Water Breathing Problems”, Underwater Magazine, July 2001

Preventative action

Warn divers of risk.

Use gas heaters for diving below 7C, and particularly below 4C.

Functional Safety Implication

Advise divers that below 7C, gas heating is required, and particularly below 4C.

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17 FAILURES SPECIFIC TO UMBILICAL-SUPPLIED DIVES

17.1 Loss of Umbilical (Commercial diver)

Means complete cutting of the umbilical, or cutting it and losing some of the services on the umbilical, such as power or gas.

Cause

Disconnection.

Heavy object falling on umbilical.

Cutting of umbilical.

Failure of topside to provide umbilical support.

Preventative action

Reduce umbilical services to the minimum: power, communications and umbilical gas feed.

Functional Safety Implication

Should be survivable by use of bail-out carried by diver. Maximum depth and maximum O2 concentration in bail-out gas determines bail-out size.

Put a transponder onto the diver. Separate to the rebreather.

Consider the external protection to avoid the reduction in diameter from increasing the risk of it being severed, but diver need to be able to cut the umbilical or disconnect the umbilical using normal diver hand tools if required.

17.2 Cut of umbilical near surface (Commercial Diver)

Cause

Disconnection.

Heavy object falling on umbilical top-side.

Cutting of umbilical.

Failure of topside to provide umbilical support.

Preventative action

Risk is the diver being sucked into the umbilical due to the pressure in the umbilical being much less than the ambient. Fit a one-way valve to the umbilical at the point where it feeds into the diver's helmet.

Functional Safety Implication

One-way valve is required.

Adequate bail-out is required. Should be survivable by use of bail-out carried by diver. Maximum depth and maximum O2 concentration in bail-out gas determines bail-out size.

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17.3 Entrapment of Umbilical (Commercial diver)

Cause

Heavy object falling on umbilical.

Umbilical floats and is caught by propellers or other moving objects in the water, causing impact between the diver and the object. That is the umbilical becomes a “fishing line” for divers.

Preventative action

Reduce umbilical services to the minimum: power, communications and umbilical gas feed so it can be moved more easily.

Diver should be trained to safeguard umbilical.

Functional Safety Implication

Umbilical should be either disconnectable or the diver should carry means to cut the umbilical to free himself.

Procedures to avoid diver entrapment. Accidents where this has occurred the procedures were not followed.

Control weight of umbilical is important, such as a line to flood.

17.4 Loss of Helmet (Commercial diver)

Cause

Inadequate attachment.

Preventative action

Use helmet that requires at least two actions using two hands to detach.

Functional Safety Implication

Entire helmet comes within Functional Safety by virtue of it containing electronic functions (microphone etc).

Monitor electronically whether a helmet is attached correctly.

Require at least two operations using two hands to detach helmet.

17.5 Sudden change in depth (Commercial diver)

Cause

Falling into a hole, or uncontrolled rise, causing intermediate pressure from umbilical gas to be either excessive or insufficient.

In bail out, the SCR has no means to add gas to the suit, or the loop. If there is a depth excursion downwards, then the diver will have squeeze.

Snagging an umbilical on lifting parachutes, thrusters, ROVs, cranes etc.

Preventative action

System should bleed off excess umbilical pressure.

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One-way valve needed in case of negative pressure.

Functional Safety Implication

1.1.41.1 Same as for umbilical being cut near surface.

1.1.41.2 The system should have an underpressure valve on the helmet, and this should allow flooding of the suit.

1.1.41.3 Train diver to descend slow enough for the SCR to fill loop.

17.6 CO in loop (Commercial diver)

Cause

Contaminated breathing gas.

Metabolism product.

Preventative action

Flush loop periodically, and test for CO.

Use only certified diving gas.

Functional Safety Implication

Use only certified diving gas, should be explicit in the user manual.

Requires active CO monitoring on the diver for very long dives.

Statoil Commercial Dive Doctor consulted specifically on this point and advised that over a 4 hour dive, the CO from metabolism products is not a safety hazard.

General diver training should cover awareness of the symptoms of CO: headache, tightness across the head, nausea, then LOC. Tainted gas smell that is apparent to the diver only after a period of breathing from the gas, is a strong sign of CO (gas smells normal to divers with only brief exposure): divers should be aware of this.

17.7 HC or Volatile Organic Compounds in Loop (Commercial diver)

Cause

Contaminated breathing gas.

Metabolism product.

Offgasing of plastics or cleaning agents in rebreather.

Detailed presentation available on this topic. Hazard depends on which HC or VOC is involved: some are only midly anesthetic, others are highly carcenoginc or hazardous to health.

Preventative action

Flush loop periodically, and test for VOCs.

Functional Safety Implication

Requires active HC and VOC monitoring on the diver.

Noted that some inorganic compounds such as hydrogen sulphide or mercury compounds are highly toxic and may also be in the breathing

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gas. Requires strict control of breathing gas, and RoHS compliant components in the dive system.

17.8 Loss of communications (Commercial Diver)

Cause

Equipment failure.

Inattentive operator.

Collision on surface.

Failure of umbilical link.

Preventative action

Use multiple communication paths.

Functional Safety Implication

SIL 0 failure. Occurs very frequently with current systems (more often than once in 1000 hours), without escallation of safety issues.

Requires at least two communication paths.

Provide communications to bell in addition to comms to surface.

Question on through-water ultrasonic comms: desirable.

17.9 Loss of Gas Heating (Commercial diver)

Cause

Electrical failure or overheating of heating element (component failure).

ESA member advised that in trials at 500m loss of breathing gas heating resulted in the diver not being able to return the bell, which was 2metres away. Another member advised that at 450m, there was hypothermia to the extent of the diver foaming at the mouth when the breathing gas temperature was reduced, but still above 20C?. This affect should be reduced considerably if the diver is on a rebreather and in a dry suit.

Massive reduction of thermal balance when diving at extreme depth if gas heating is lost.

Preventative action

Should be redundant systems for breathing gas heating.

Functional Safety Implication

Breathing gas heating should be considered as a SIL 1 action for a diver using a rebreather with a dry suit.

Use a dry suit with a rebreather, so loss of heating is not catastrophic.

17.10 Overheating (Commercial diver)

Cause

Helmet overheating or suit, from insufficient thermal losses. Thelma AS report 06-20 simulations show in 4C sea water, hard working diver

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in 250gm undersuit with clo value of 4.5, overheats to body temperature above 44C in 200 minutes.

Preventative action

Diver should be able to flush the helmet and suit.

Functional Safety Implication

Full safety case required for diver thermal balance.

Special consideration in warm water conditions. Severe problem in Persian Gulf and other near tropical conditions.

17.11 Loss of Suit Heating (Commercial diver)

Cause

Electrical failure.

Preventative action

Use sufficient passive thermal protection to return to the bell.

Functional Safety Implication

State requirement for passive undersuit thermal protection in user manuals and training.

Treat gas heating as a SIL-4 requirement for very deep diving.

17.12 Excess suit heating (Commercial diver)

Cause

Electrical failure or excessive water temperature (hot water suits).

Extensive reports of 3rd degree burns in divers using electrically heated suits in the early 1970s. Divers do not realise they are burning, when under pressure: divers involved in use of these suits interviewed.

Hot water suits have uneven heating and divers are not aware of the high water temperatures. Many divers report burns.

Top-side operator error.

Divers in bell overheat while waiting to go diving.

Preventative action

Electrical: use a SIL 4 rated heating system.

Functional Safety Implication

Eliminate failure mode by use of self-regulating materials, and use of active current monitoring to detect shorts or excess current drain, in a SIL 4 design.

17.13 Tools and Equipment (Commercial diver)

Cause

Any cutting or grinding tool, slipping onto the diver or his equipment.

Burning and welding, causing hot residue.

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Oxy-arc cutting blowback pushes out the lexian glass in the helmet or cracks the helmet.

Oxy-arc cutting blowback Hydraulic pulse on membranes and on hoses.

Oxy-arc cutting blowback Igniting oxygen pockets while burning.

Sand and grit blocking valves and orifices for equalisation.

Electrical currents increasing corrosion through electolysis.

Do the EMS limits in CE directives, cover high current densities seen in diving? The current is enough to strip the chrome from the brass regulators used on Kirby Morgan helmets, and enough to shutdown the microphone circuits in the helmet while these operations are carried out.

Mechanical vibration from a jack hammer, transmitted through the diver to the equipment.

Noise from high pressure water jets.

Towing heavy weights over the shoulders rubbing on the suit and counterlungs.

UV from diving welding, or the ozone this creates in a habitat that has had recent welding.

Dressing on and off in a safe manner in a habitat.

Diving in extremely oily conditions where the diver has to undress in the water, then move with the helmet into a decontamination bell. Concern over nooks and crannies making it difficult to decontaminate. Contamination in the wind of the umbilical.

Preventative action

Electrical: use a SIL 4 rated heating system.

Include extreme induced current test in system evaluation.

Functional Safety Implication

Test the equipment for operation between a pair of underwater burning system electrodes in use (actual burning). Measure the field.

The EMS limits in CE directives do not cover the high current densities seen in diving, so test using the highest possible current density with the unit in water.

Shield all internal electronics for magnetically induced currents.

Consider use of liquid crystal electrolytic materials such Kynar for the electronics shell, to form a Faraday shield around the electronics in the presence of intense underwater electrical currents.

17.14 Oro-nasal one-way valve failure (Commercial diver)

Cause

Failure to check valve pre-dive, or umbrella valve stalk failure: it may be missing, inverted or damaged.

Preventative action

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Check oro-nasal one-way valve before every dive.

Functional Safety Implication

Retained CO2 issue.

17.15 Gas manifold one-way valve failure (Commercial diver)

Cause

Top gas manifold on a commercial rebreather routes the bail out gas to the injector when the main umbilical gas supply fails. The main umbilical is a breathable gas, the bail out gas is not: the PPO2 is too high. One way valves prevent the bail out gas flowing into the umbilical supply, where it would increase the PPO2 of the gas the diver breathes via either helmet freeflow or demand valves, or by auto-loop-volume devices.

The problem cannot be mitigated by lowering the PPO2 in the bail out, without reducing considerably the duration of the bail out at extreme depth. For example, at 600msw, the diver may be breathing a gas with only a few percent of O2, so to add O2 to the loop a lot of Make-Up-Gas is expelled. This means the amount of bail out gas for extreme depths is unreasonably large, if the bail out is breathable. Instead the problem is mitigated by use of two one-way valves in series.

These one-way valves shall operate with a very high absolute pressure, but a low differential pressure. Most one-way valves that can withstand a full tank blowout pressure (300bar), rely on 4 bar of more of differential pressure to shut them. In this case, the valves operate at 2 bar so normal one-way gas valves leak.

Where a commercial rebreather is supplied with pure O2 in the umbilical, then leakage of the one-way valves would result in the diver being supplied with pure O2 by the ALV, a critical failure that requires rapid intervention to prevent the diver's PPO2 rising to dangerous levels (such as the ALVBOV switching the diver to open circuit, or the diver switching to freeflow).

Preventative action

Prevent by appropriate design. If failure occurs, diver shall bail out immediately.

Functional Safety Implication

1.1.41.4 A singular one-way valve would be a single point of failure, so there need to be two of them in series.

42. The one-way valve need to be properly characterised so it operates with the desired pressure drop: this is at most 2 bar. The ideal valve would operate with 0.1 bar.
43. The operation of the one-way valves should be a pre-dive check.
44. An ALVBOV is highly desirable as a rapid bail out system.

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17.16 Loss of Umbilical Gas

Cause

Umbilical cut, turned off, crushed, folded or disconnected.

Symptoms

Surface

Diver's free flow test fails.

Dive

Diver should abort dive without descending.

Functional Safety Implication

Same as make-up-gas gas supply failure.

17.17 Bail-Out Gases Used instead of Oxygen

Cause

Flow restriction in oxygen hose causes one-way valves to provide bail out gas.

Rebreather without one-way valves or interlocks, has switchable manifold, which is switched to a position without a gas supply or incorrect gas supply.

Symptoms

Surface

PPO2 low.

Dive

PPO2 varies and generally low.

Recovery action during Dive

Bail out.

Preventative action

Check worst case pressure in manifolds.

Functional Safety Implication

Ensure manifolds are checked for pressure with worst case O2 flow.

Do not use diver switchable manifolds.

Provide pressure sensors for umbilical O2 gas.

18 DIVER PHYSIOLOGY RELATED FAULTS

Functional Safety requires that operator failures are managed by the safety system: that is the system need to be designed for use by human beings, with all their physiological, phsycological and idiosyncratic limits.

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It is totally unacceptable to design a life support system that works if operated by an automaton, but does not manage safely the operator failures that can be identified from accident studies, incident studies or are apparent from HAZOPs.

Unfortunately, many divers expect others to be perfect: following an accident, they may state “he should have checked his PPO2”, “he should have done XXX”. In expressing this view, they are expressing a complete ignorance of safety engineering. ALL diver errors need to be managed safely, where there is a means to do so at reasonable cost: the ALARP principle.

18.1 Hypoxia

Cause

Breathing gas contains less than 16% of O2.

Symptoms

Surface

Anaethesia

Reduced awareness

Sudden Loss of consciousness (time, activity and diver dependent, but typically around a PPO2 of 0.065 atm).

Dive

As on surface.

Recovery action during Dive

Bail out.

Preventative action

Force bail-out automatically if user does not act on warnings.

Eliminate electronic controller failures modes that are not fail-to-safe state.

Functional Safety Implication

Apply Functional Safety life-cycle process appropriate to SIL assessment.

Implement a fail-safe automatic shut off valve; bail-out is essential.

See all faults relating to Hypoxia herein, and also Sudden Underwater Blackout (Fault 18.18)

18.2 Hyperoxia

Cause

Breathing gas contains excessive PPO2 for exposure duration.

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Diver's O2 tolerance is compromised by retained CO2.

Symptoms

Surface

Visual narrowing, muscle spasms (twitching), followed by seizure.

Dive

As on surface.

Recovery action during Dive

Bail out to a low PPO2 gas. Note "off effect" may bring on a seizure.

Preventative action

Force bail-out automatically if user does not act on warnings.

Eliminate electronic controller failures modes that are not fail-to-safe state.

Track CNS and Pulmonary O2 exposure, weighted for CO2

Functional Safety Implication

PPO2 control is a critical function.

Track diver's CNS and Pulmonary O2 exposure.

18.3 Hypercapnia

Cause

Scrubber failure, from unexpected scrubber failure or from diver extrapolating actual scrubber duration.

Excessive Work of Breathing

Poor diver breathing pattern.

Diver underlying illness

Scrubber seal failure.

Scrubber bypass.

Symptoms

Surface

Headache

Agitation.

Hallucinations.

LOC.

Dive

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As on surface except there may be no headache. LOC often followed by drowning.

Recovery action during Dive

Bail out.

Preventative action

Force bail-out automatically if user does not act on warnings.

Mitigate by design and training.

Functional Safety Implication

1. Monitor exhaled CO2 to monitor retained CO2: this is the most direct reading of the diver's blood CO2 level that is practicable.
2. Monitor scrubber life with the application of ALARP.
3. Monitor scrubber health with the application of ALARP.
4. Minimise WOB with the application of ALARP.
5. Reduce variation in scrubber duration from filling method or variation in scrubber chemistry (e.g. different granules).
6. Design scrubber to have uniform endurance with depth and temperature, with the application of ALARP.
7. Provide 2kPa scrubber endurance ratings (in addition to 0.5kPa and any other regulatory levels) so diver knows the practical duration of the scrubber and does not extrapolate from a figure which is meaninglessly low from a diver's standpoint.

18.4 Breathing off loop that otherwise cannot sustain life

Cause

User fails to bail out.

Frequent cause of fatalities on CCRs.

Diver may not see, be aware of, or be able to react to alarms because they are impaired by:

- Narcosis
- Hypoxia before LOC
- Barotrauma
- Stress
- CO2 retention
- User may be deaf and not hear the alarms (implicated in a dive fatality).
- Training on an SCR that does not require the user to monitor the PPO2 in the

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breathing loop (implicated in an eCCR dive fatality)

- Malfunction of the electronic controller
- Absence of function of the electronic controller

Symptoms

Surface

Anaethesia

Reduced awareness

Loss of consciousness.

Dive

Anaesthesia

Reduced awareness

Loss of consciousness.

Recovery action during Dive

Bail out.

Preventative action

Force bail-out automatically if user should not act on warnings.

Eliminate electronic controller failures modes that are not fail-to-safe state.

Functional Safety Implication

Implement a fail-safe automatic shut off valve; bail-out is essential.

18.5 Allergic Reaction to Material

Cause

Use of latex or other allergenic material. Repeated exposure to latex can trigger severe allergic reactions and sensitivity to other materials.

Foreign matter in loop, especially mouthpiece, such as from jelly fish.

Off-gassing of noxious compounds has been identified as the cause for nausea in deep saturation dives.

Symptoms

Surface

Can vary from difficulty breathing, burning around mouth through to toxic shock, which can be fatal on the surface.

Dive

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Same as on surface.

Nausea.

Loss of consciousness, death.

Recovery action during Dive

Bail out

Preventative action

Ensure products do not contain any allergenic materials.

Use mouthpiece retainer or full face mask to mitigate risks if diver is unconscious.

Functional Safety Implication

Eliminate all allergenic materials from loop.

Check all materials carefully for off-gassing components both from the MSDS and from rigorous materials testing.

Latex is particularly insidious because it appears to be able to create a sensitivity to other materials, creating allergies to common materials: this is a serious problem for health workers using latex gloves, so should be avoided in rebreathers.

In 1997 the FDA required labelling of medical devices containing NRL. FDA also prohibits the use of the word hypoallergenic on labelling of devices containing natural rubber[5]. In 1999,OSHA issued a technical information bulletin to alert field personnel to the potential for allergic reactions in some individuals using natural latex gloves and other products made from the material[6].

The US Consumer Product Safety Commission (CPSC) is considering a petition to rule NRL a strong sensitiser under the Federal Hazardous Substances Act. That designation indicates that a substance has significant potential for causing hypersensitivity. The petition claims that individuals have developed latex allergies or suffered allergic responses through exposure to NRL in consumer products[7].

18.6 Vomiting into breathing loop

Cause

Contaminated breathing gas.

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5 US FDA, Federal Notice Register, Final Rule: Natural Rubber – Containing Medical Devices, User Labelling, 62 FR 189 51021-51030, 30 Sept 1997

6 OSHA Technical Information Bulletin, Potential for Allergy to Natural Rubber Latex Gloves and other Natural Rubber Products, 12 April 1991

7 Unified Agenda of the Consumer Product Safety Commission, Federal Register, 65 FR: 231 74830-74839, 30th Nov 2000

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Sea sickness.

Alcohol, drugs or ill health.

Divers being sick underwater occurs frequently.

Preventative action

Use certified breathing gas.

Do not dive under influence of alcohol or drugs.

Do not dive in case of bad health.

Maintain an O.C. regulator to be sick through.

Functional Safety Implication

It is beneficial to have an O.C. regulator in the system. This would require a breathable gas at all times.

A combined ALV/BOV, which is always in the loop, is highly desirable. It would enable the diver to be sick with switching gas supplies. This will not be able to be cleared as an O.C. regulator can be, but gives a large path for material to be purged. It is desirable that there be a method for introducing water into the loop for this purpose: such as from a drinking tube, then from the diver to the ALV/BOV.

Requires breathing hose of sufficient diameter so as not to be blocked by vomit. Experiments using frozen carrots and sweet corn in yoghurt (20%,20%,60%) indicate that a 36mm diameter hose and fitting is required. The web around the mushroom valve is particularly liable to be blocked. The number of fingers in the web should be kept to the minimum subject to the mushroom valve not folding under the finger lip.

18.7 Deco dive with incorrect PPO2 level in loop

Cause

User error and design omission allowed the user to calibrate the CCR as if it was 98% O2, when PPO2 level in the loop could have been as low as 48%. Result was Cat III DCI.

Preventative action

All O2 Cells should calibrate in air when the unit is open: users should not be asked to calibrate with a gas supply which may not in itself be calibrated, injecting an uncalibrated amount of gas into an uncalibrated loop volume (the procedure used by the manufacturer).

Functional Safety Implication

Eliminate problem by calibrating on air.

18.8 DCS risk higher than statistical projection of deco algorithm

Cause

Bugs in deco software, especially in handling constant PPO2.

Inherent risk of deco algorithm used not assessed properly.

Other health problem leading to predisposition to DCS.

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Preventative action

All decompression software should be formally verified to prove that the algorithm implemented is actually that intended.

Full, regular health check-up. Screen for health problems known to increase DCS risk.

Functional Safety Implication

Verify the deco algorithm is implemented correctly using formal methods.

18.9 Respiratory collapse from WOB

Cause

Excessive Work of Breathing or breathing resistance

Preventative action

Work of Breathing should be well within the standards required by standards. It is noted that the permitted Work of Breathing is being reduced in future standards as a result of work by NEDU and Qinetiq on the physiological effects of work of breathing on divers.

Functional Safety Implication

Achieve lowest practicable Work of Breathing.

18.10 Respiratory collapse from thermal respiratory shock

Cause

Gas in dive cylinder is cooled by 30C by expansion from first stage, which can result in cold gas being inhaled when the ambient temperature is below 7C. See B. Morgan, P. Ryan, T. Schultz and M. Ward, "Solving Cold Water Breathing Problems", Underwater Magazine, July 2001

Preventative action

Warn divers of risk and to manage it in the same manner as respiratory collapse from water inhalation below.

Use gas heaters for diving below 7C, and particularly below 4C.

Functional Safety Implication

Advise divers that below 7C, gas heating is required, and particularly below 4C.

18.11 Respiratory collapse from asthma

Cause

Diver asthmatic attack.

Preventative action

People with known asthma should not dive.

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However, asthmatic attacks can occur for the first time in diving: the result is very similar to that of respiratory collapse from water inhalation, and should be handled in the same manner underwater.

Functional Safety Implication

Follow recommendations for Respiratory Collapse General.

18.12 Respiratory collapse from water inhalation

Cause

Even in snorkelling, inhalation of water can cause a respiratory collapse: the diver inhales a small amount of water and feels like he is suffocating or drowning, with wheezing inhalation. The risk is much higher where water salinity is high: for example, in the Red Sea – a few drops of salt water inhaled can cause the diver's throat to constrict with the diver coughing out water.

Preventative action

There are training, operational and design actions required. See Respiratory Collapse (General).

Functional Safety Implication

1. A dry breathing regulator shall not suddenly give a wet breath.
2. Exhaust valves need to be of the mushroom type, not the flat type to ensure they do not allow water into the DSV.
3. The training material should explain the imperative of checking that exhaust valve diaphragms are not folded or otherwise compromised.

Follow recommendations for Respiratory Collapse (General).

18.13 Respiratory collapse from pressure surge

Cause

Hitting the purge button from a high flow regulator or DSV, when it is in the diver's mouth.

Preventative action

See Respiratory Collapse (General).

Functional Safety Implication

Limit the purge flow rate on rebreather DSVs and regulators.

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18.14 Respiratory Collapse (General)

Cause

Multifactorial: see Respiratory Collapse from water inhalation, asthma, pressure, WOB, Immersion Pulmonary Oedema, or directly to cardiac arrest from hypoxia and death.

Preventative action

There are training, operational and design actions required to handle respiratory collapses – these appear to occur frequently in divers.

In training: The diver needs to be trained what to do when a respiratory collapse occurs, namely:

1. Secure themselves so if a loss of consciousness occurs, the diver will not sink down or rise up – a buddy can be very helpful in this, or attachment to a nearby structure.
2. The diver shall not ascend rapidly to the surface, as without the ability to exhale properly, the accident can progress to a fatal embolism very easily.
3. The diver shall stop movement to reduce the metabolic demand on oxygen.
4. The diver needs to remain calm and breathe in very slow deep breaths, in and out, until their respiration becomes normal, which may be as long as five or ten minutes. The diver will feel starved of air, but air will be exchanged and the diver can survive so long as the RMV is kept below the amount that can pass through the collapsed trachea.

A respiratory collapse is a very dangerous event, that can progress to drowning, panic attack, or Immersion Pulmonary Oedema, so should be addressed immediately by the above actions.

In operation: exhaust valves and mouthpieces need to be cleaned and inspected after each dive.

In design: implement the Functional Safety Implications listed below.

Functional Safety Implication

1. Mouthpieces require retainers so they stay in the mouth even if a Loss of Consciousness occurs.
2. The training material should describe how to respond if respiratory collapse occurs, from any of the sources.

18.15 CNS Toxicity

Cause

1. Failure of PPO2 controller (not meeting Functional Safety).
2. Serious PPO2 spiking during descent.
3. Injecting O2 instead of Make-Up-Gas.
4. Diver bailing out on to O2 instead of on to Make-Up-Gas or off-board bailout.

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5. Incorrect use of CNS calculation. Original papers describing CNS calculation are based on a 4% reduction in vital capacity with 100% CNS loading (Oxygen Toxicity Calculations. E. Baker). NUI research paper indicating 1% of users having CNS toxicity effects at 75% CNS loading. Despite this, users believe they can tolerate 100% CNS loading as a basic plan: some report regular dive planning with 175% and 250% CNS loading.

Preventative action

CNS clock in common use has CNS convulsion incidents reported at as low as 25% CNS loading.

Original paper on CNS measures loss of lung surficant as primary measure of CNS damage, with 1% at 75% CNS clock and 4% at 100%. Use less CNS clock.

Functional Safety Implication

Modified CNS algorithm, with margin to reduce statistical incidence of measurable CNS damage. Published on DL Web Site, and on Rebreather World, with formal model to enable implementation to be verified.

CCR controller should track CNS and maintain within safe limit, by adjusting PPO2 set point if necessary.

Provide a Chicken Switch for the commercial diver using a helmet, as loss of speech is one of the first indicators of CNS (from interviews with CNS tox victims).

There should be no measurable loss of lung surficant during a dive. This requires downrating the CNS clock as above.

This is a critical failure that has caused more than one death.

Eliminate all scrims in the design.

Eliminate scrubber packing variance.

Use EAC scrubber to eliminate change in breathing resistance during use.

Measure WOB actively pre-dive and during the dive, and warn user.

Measure respiratory parameters and warn the user when these move outside normal or safe ranges.

18.16 Pulmonary O2 Toxicity

Cause

High PPO2 for long period (multiple dives, or extremely long dives).

Preventative action

Diver should monitor pulmonary O2 toxicity when doing large numbers of dives.

Instruct diver to take a day off every fifth day covers most recreational settings.

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Functional Safety Implication

Provide instruction and information on pulmonary exposure risks.

18.17 Counter-diffusion hazard

Cause

Use of breathing gases with END less than 0msw.

Use of different gases between suit and breathing loop.

Switching between gases with different constituents.

Preventative action

Training on hazards of counter diffusion.

Functional Safety Implication

Measure N2 by deduction of other gases, and give alarm if less than 500mbar of N2.

State hazard clearly in training manuals.

18.18 Sudden Underwater Blackout

Cause

Shallow water blackout and Deep water blackout are phenomena which occur due to hypoxia or hypocapnia in breath-hold divers (freediving) and is outside the scope here other than for a comparison of the process with the SCUBA equivalent.

Hypoxia and hypercapnia are by far the predominant causes of sudden loss of consciousness on rebreathers, however there are rare occurrences on Open Circuit. These may be due to gas expanding in decompression sufficiently to block blood supply, and can occur in very poor decompression management (such as in emergency ascents where the diver has a large decompression obligation).

Underlying health issues are very unlikely to cause blackout underwater, but should be considered in each case it occurs.

Shunts can reduce the PPO2 in the oxygen cascade from inhalation to the tissues, as does hypoventilation: each can exacerbate hypoxia risks.

Preventative action

Always dive with a buddy.

On rebreathers, bail out to open circuit on ascent.

On rebreathers, in an emergency ascent, do not inhale from the breathing loop.

Functional Safety Implication

The cause of sudden blackout is almost always hypoxia, though underlying health issues should always be considered.

Most people become unconscious when the PPO2 in their lungs, normally 0.21 atm falls below ~0.075atm: the alveolar PPO2 is around

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2/3rd of this level due to the oxygen cascade whereby there is a reduction in PPO2 as the gas is warmed and humidified in the trachea, and is under a slight vacuum – for simplicity we shall refer to the PPO2 in the inhale gas as that is what is relevant for the SCUBA diver.

This mechanism by which the PPO2 falls below 0.075 atm (equal to 0.04 atm at the alvaeoli), is different between freedivers, SCUBA divers and rebreather divers:

For the freediver, ten metres of water effectively doubles the minimum PPO2 to avoid LOC to 0.15atm, then when the diver ascends, the PPO2 falls putting them below the 0.075 atm limit. A PPO2 of 0.12 atm at ten metres in a freediver's lungs, will pretty much ensure a blackout between four metres and the surface. Although comfortable on the bottom the diver may actually be trapped and unaware that it is now no longer possible to ascend without becoming unconscious without warning before the diver can reach the surface.

For the Open Circuit SCUBA diver in a free ascent (i.e. emergency ascent, exhaling), the limits are similar to those of the freediver. If the gas inhaled is air, then if the SCUBA diver were to return instantly to the surface, their lungs would contain an alveolar pressure equal to that when a gas is inhaled having a PPO2 of 0.21 atm. However, during the ascent, the diver metabolises some of the gas causing the PPO2 to fall. If the ascent is less than a minute, this effect is not sufficient to cause hypoxia, but it does become and issue if the ascent is slow. Fortunately for the SCUBA diver, if the regulator is kept in the mouth, the reductions in ambient pressure on ascent will give the diver the ability to take a few breaths of gas while ascending, avoiding any hypoxia risks.

For the Closed Circuit SCUBA doing an ascent, where the PPO2 is the same as that of air at the same depth, a much greater risk exists because the diver may not feel the urgency to ascend as there is still a breathable loop volume. If the diver takes a minute to ascend from 10m, and is breathing normally during the ascent, the reduction in PPO2 will be sufficient for the diver to lose consciousness just below the surface. Fatal accidents have occurred for this reason. To avoid this risk, the rebreather diver shall bail out onto Open Circuit, or simply may a buoyant ascent and exhale, if the rebreather is not providing additional oxygen.

Related risks where oxygen may be lost from incorrect positioning of OPVs on rebreathers further extends this hazard to rebreathers where there is an oxygen supply. These accidents require detailed formal modelling to conclude the cause, but in some cases, it is due to an ascent blackout as the injected oxygen was not conveyed to the diver due to flow reversal as the volume of the gas in the counterlungs expand faster than required to meet the diver's the respiratory volume.

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18.19 Immersion Pulmonary Oedema (IPO)

Cause

A phenomenon that is not fully understood but seems to be multifactorial in cause, the end result of which is , is fluid accumulation in the air spaces and parenchyma of the lungs.

IPO leads to impaired gas exchange and may cause respiratory failure, leading to cardiac arrest from hypoxia and death.

The primary symptom is difficulty in breathing.

IPO appears not to be related to diver fitness, O.C. or CCR, hydration levels, work levels, blood hypertension, or medication such as beta blockers, but is connected with diving[8] [9].

The cause of pulmonary edema in the presence of a hypertensive crisis is thought to be due to a combination of increased pressures in the right ventricle and pulmonary circulation and also increased systemic vascular resistance and left ventricle contractility increasing the hydrostatic pressure within the pulmonary capillaries leading to extravasation of fluid and oedema.

IPO can be caused by an upper airway obstruction (negative pressure pulmonary oedema), such as a high WOB or a high hydrostatic pressure[10].

IPO appears to be related to the heart having a high pre-load or post-load. In diving this can occur because of:

1. The centralisation of the blood volume at the same time as a reduction in the hydrostatic resistance in the body: instead of blood having to be pumped up and down a column which may be 2m in height, when a person is diving the hydrostatic differences across the body is very low. However the condition does not seem to be triggered by a person sleeping, in a prone position, in a cold environment: which similarly centralises the blood volume and reduces hydrostatic load.
2. Increased WOB.
3. Increased hydrostatic load: a front mounted counterlung is preferred to a back-mounted counterlung.

Preventative action

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[8] Hampson NB, Dunford RG (1997). "Pulmonary edema of scuba divers". *Undersea Hyperb Med* **24** (1): 29–33. PMID 9068153. Retrieved 2008-09-04.

[9] Cochard G, Arvieux J, Lacour JM, Madouas G, Mongredien H, Arvieux CC (2005). "Pulmonary edema in scuba divers: recurrence and fatal outcome". *Undersea Hyperb Med* **32** (1): 39–44. PMID 15796313. Retrieved 2008-09-04.

[10] Papaioannou, V.; Terzi, I.; Dragoumanis, C.; Pneumatikos, I. (2009). "Negative-pressure acute tracheobronchial [[hemorrhage]] and pulmonary edema". *Journal of Anesthesia* **23** (3): 417–420. doi:10.1007/s00540-009-0757-0.

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1. If a diver has difficulty breathing, then they should assume an upright position, take very slow and exceptionally deep breaths in and out. A diver that cannot breathe properly should NOT ascend.
2. Switching to an alternative gas source is recommended.
3. If a person has suffered an IPO event, then use of a rebreather is counter-indicated. That is, the person should not dive rebreathers.
4. Optimisation of parameters that are implicated, without waiting for the scientific understanding to confirm these. In particular WOB, counterlung elastance and hydrostatic imbalance should be optimised.

Functional Safety Implication

WOB, counterlung elastance and hydrostatic imbalance should be optimised.

If the primary rebreather is a back-mounted counterlung, then a rescue rebreather should use a front-mounted counterlung.

19 GENERAL DIVING HAZARDS

Sports diving in general seems to have a risk of accident of between one in 10,000 hours to one in 100,000 hours, depending on the type of diving being carried out [3], [4]. Some of these accidents are due to equipment failure [6], most are due to lack of training, lack of attention, poor judgement or the effect of an underlying illness or predisposition. Use of rebreathers has considerably higher risks based on the same accident figures and the population of rebreather divers. The increase appears to be associated with failures to meet Functional Safety in the equipment design: the rebreathers with the shortest MTBCF have the highest rates of fatal accidents, and rebreathers with the best MTBCFs have the lowest rate of fatal accidents.

Commercial rebreather diving seems to have a significantly lower accident rate than sport rebreather diving, based on IMCA accident reports [5] and the amount of commercial diving carried out. Commercial diving has had a much larger amount of research carried out into the health and safety of divers than is the case for sports divers.

All diving carries some short and long term risks to health.

Long-term risks are described by D.H. Elliott & R.E. Moon [1]. All long-term health risks appear to originate from an event that can also give rise to a short-term risk, such as an untreated DCS or barotrauma. In some cases the long-term risk is due to a succession of minor insults, in other cases, from the effect of cellular damage from a single insult which may, at the time, have appeared insignificant.

Short-term risks are compiled from D.H. Elliott & P.B. Bennet [2], DAN and BSAC accident reports, as follows:

Health Risk	Cause and effects

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Respiratory Gases	Contaminated breathing gas, with effect of narcosis, anaesthesia, illness. Divers who feel normal on the surface and feel nausea underwater may have CO poisoning. Unsuitable breathing gas for depth: hypoxic or hyperoxic, with effect of loss of consciousness, convulsions Narcotic breathing gas with effect of loss of judgement, time perception, consciousness. Insufficient gas, with effect of drowning. Gas switch between gases with large difference in anaesthetic effect, with effect of loss of consciousness. Counter-diffusion with effect of DCI.
Diving Reflex and Sudden Death Syndrome	Water contact on forehead has effect of "Whale Diving Reflex", with constriction of blood vessels, slowing of heart beat and increase in blood pressure. Implicated in Sudden Death Syndrome in older divers. Effect also increases probability of acute cardiac illness and of strokes, where there is a further increase in blood pressure due to a high retained CO2.
Thermal Balance	Lack of thermal protection, with effect of hypothermia or aborted dive with decompression load. Suit leaks without means to heat the suit cause hypothermia. At extreme depths, loss of thermal energy from the lungs.
Exhaustion	Swimming against strong current, effect of loss of energy to remain afloat.
Loss of Buoyancy Control	Loss of buoyancy control with effect of uncontrolled ascent or descent. Entanglement in surface towed objects with effect of loss of buoyancy control, causing DCS, barotrauma or drowning. Entanglement with object moving towards surface, such as a lift bag or SMB reel, with effect of loss of buoyancy control, causing DCS, barotrauma or drowning. On surface, diver fails to drop weight belt when in difficulty, with effect of drowning. Failure of BC valves with effect of uncontrolled ascent or descent. Confusion by diver causing diver to press inflate button when intends to deflate, or vice versa, with effect of uncontrolled ascent or descent. Weight jackets may redistribute weight, causing diver to be "up-ended", with effect of drowning. Simple weight belts should be encouraged, with retainer to prevent accidental loss.

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	Loss of control of dry-suit gas may cause diver to by "up-ended", which, without training, the diver may not recover from. Recovery method is simply to form a ball and roll out. If diver does not succeed, then effect may be drowning.
Disorientation	Illness, vertigo, reduction in visibility, unfamiliar environment with effect of panic or behaviour leading to entrapment or becoming separated underwater. Ultimately effect may progress to drowning from insufficient respiratory gas, or barotrauma from loss of buoyancy.
Perceptual Narrowing	Stress, leading to information essential for safety being ignored.
Panic	Predisposition, asthma, lack of training, with effect of excess use of respiratory gas, behaviour contrary to safety.
Barotrauma	Breath-holding during ascent, from as little as 1.2m, with effect of gas embolism. Loss of buoyancy leading to pulmonary barotrauma, alternobaric vertigo, compression barotrauma, or any embolism. Illness causing gas blockage, with effect of embolism on lungs. Prostheses or dental cavity, with effect of acute pain.
DCS	As per CCR hazards.
Dehydration	Serious sea-sickness, or alcohol abuse, drugs, poor hydration practice, with effect of increased DCS risk and may have effect of loss of consciousness in extreme cases.
Heart Attack or Stroke induced by unaccustomed exercise	May be induced by Dive Reflex. May be induced by CO2 retention, or a combination of these two phenomena. Risk is higher with dry suits or hot water suits, Trimix (carrying multiple tanks), on a RIB or ice diving compared to diving from a hard boat, and in cold water. Effect is invariably drowning.
Military Sonar	Sports divers have been attacked by the military sonar of nuclear submarines when carrying out a dive and a submarine has been in the facility in the English Channel. Divers felt very nauseous to the point of passing out. Evidence that nuclear submarines view any diver in the vicinity as an attack and have a policy of killing the diver. A fatal accident in 1998 of a diver on a rebreather implicated military sonar from a nuclear submarine as one of two possible causes. Video footage from 1998 North Pole Expedition supplied.

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Unconsciousness	Asthma, epileptic fit, insufficient or unsuitable respiratory gas, oxygen convulsion, CO2 retention, illness, generally with effect of drowning. See Fault 18.18
Underwater explosions	Proximity to naval exercises, or commercial demolition. Effect is pulmonary and intestinal rupture and haemorrhaging. Oil exploration using seismic devices can cause severe pain and damage to divers over long distances: ten miles or more from the site of the explosion.
Underwater electric current	Commercial operations, leading to involuntary spasm and likely drowning. Note that where an accident has occurred due to underwater currents the electrical equipment should be checked in an active plating bath in addition to normal swept frequency testing to verify the equipment behaved correctly in that environment, so the two causes of accident (direct shock and equipment failure due to the current density) can be separated. A failure of the ground contact during commercial underwater cutting and welding operations can create sufficient electro-magnetic fields to be sufficient to super-heat teeth fillings even when the diver is inside a commercial helmet: electronics should be tested in these conditions: fields of 30,000 amps per square metre or more.
Venomous marine life	Contact with any venomous sea life, particularly jelly fish, stonefish, some octopus, sea snakes, conch shells, parasites. Effect: shock, pain, nerve damage, or in case of parasites, damage to internal organs or brain months after the dive.
Predators	Rare, with bites from large sharks, rays, squid, eels or seals.
Hard impacts	Impact with boats, propellers, divers falling on divers below, on to rocks in surf or heavy waves, with effect of trauma.
Excess Mechanical Shock or Strain to bone	Carrying excessively heavy objects or poor lifting technique, with effect of bone fracture, breakage, or arthritis, osteonecrosis, muscle strain. Stress can greatly increase risk of DCI damage to the bone. Cold water can increase risk of stress causing permanent damage, due to reduced blood flow. Nodules forming on bone, particularly the ear, neck and spine, as a response to cold water exposure may press on nerves, or interfere with normal joint movement.

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20 SAFETY PROCESS FAILURES

20.1 FMECA Incompleteness

Cause

All FMECAs are incomplete: knowledge is extended gradually, and at any point in time, there will be failure modes that the most rigorous review will not detect – these generally involve interfaces between the operator, the environment and the equipment.

Prevention

Mitigation is by regular review of safety data, and supplementation of the FMECA.

Functional Safety Implication

At least annual review of the FMECA is required.

20.2 Incompetent or negligent developer

Cause & Prevention

Developer not aware of safety requirements, and has not accessed or applied Functional Safety standards, or neglects to apply the required safety processes: there is no bound to the presumption of salesmen that think they are safety engineers and need no training[11]

Functional Safety Implication

Functional Safety and CASS templates state specifically the qualification requirement for developers.

CASS templates require the IEE/BCS grades be applied, increasing with increasing SIL level. This implies MIEE may be acceptable for low SIL, but FIEE is required for high SIL (SIL 2 and above). The requirement for FIEE / FIET or national equivalent at SIL 3 and above is confirmed by CASS auditors.

All other competence and training issues are stipulated by EN 61508:2004.

Engineering staff working on project need to be assessed against this.

20.3 Incompetent or falsified certification

Cause & Prevention

[11] See J. Kruger & D. Dunning, "Unskilled and Unaware of it: How Difficulties in Recognising Incompetence Lead to Inflated Self-Assessments", Journal of Personality and Social Psychology, 1999, Vol 77, No 6, pp 1121-1134. Rebreathers electronics and software developed by salesmen who have never attended any engineering course, managed by Project Leaders who never had any formal education after the age of 16 have been sold by the thousand. There is strong statistical and case evidence that this has resulted in deaths comparable to the world's worst serial killers.

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Certification body fails to ensure standards are applied, or fails to react to information such as claims that a product complies with a particular standard when that has not been proven by audit, resulting in users being misled as to the safety of the product. In some cases, this has lead to very dangerous equipment being sold to the public in large volumes.

Implication

A Safety certification body has a strong ethical and moral responsible for failures resulting from issuing certification to non-compliant equipment.

Manufacturers have a responsibility to ensure the safety certification body is fully informed of all relevant safety data, or absence of it.

Failure of an electronic or programmed part of a rebreather to meet an international Functional Safety standard, such as EN 61508:2004 Parts 1 to 3, is incompetence and negligence from a safety engineering perspective.

21 SEVERITY AND RISK ASSESSMENT

The majority of faults listed can result in severe injury or a fatal accident if not mitigated. Some faults can result in fatal accident affecting multiple people: a cylinder explosion or oxygen fire are examples.

Fortunately, most faults can be either eliminated entirely by design, or mitigated substantially through a combination of design, training and maintenance. The table overleaf identifies the residual risks following all reasonable mitigating actions. There is an inherent risk in diving, but from the table the probability is low.

In assessing probability, where a risk can be eliminated by design, then the probability of the risk remaining is zero. Where the risk must be mitigated by training alone, then the risk remaining is taken to be 1 per 10,000 hours due to the human error element of a lone user. Where the risk must be mitigated by maintenance alone, then the risk is taken to be one per 100,000 hours as the practice is to perform the maintenance and a second person check the maintenance.

The Risk tabulated is number of diver/years per incident. The probability is taken from accident studies and incident reports, or where there is insufficient data, from assessments made using HAZIDs under management by the Safety Review Group.

Fault	Eliminate or Mitigate By			Annual Risk After Mitigation		
	Design	Training	Maintenance	Severity	1/Probability	Risk
5 Gas Supply Containment Failures						
5.1 Cylinder explosion	✓	✓	✓	256	10^5	
5.2 Carbon Wrapped Cylinder Electrolysis	✓		✓		10^6	
5.3 Plastic Core Decomposition	✓				0	

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Fault	Eliminate or Mitigate By			Annual Risk After Mitigation	
	Design	Training	Maintenance	Severity	1/Probability Risk
5.4 Carbon Wrapped Cylinder Core Delamination	✓		✓		10^8
5.5 Oxygen fire from detritus in cylinder	✓	✓	✓		10^8
5.6 Cylinder Valve Failure					
5.7 Cylinder Valve O-ring or Regulator O-Ring Failure	✓	✓	✓		
5.8 High Pressure Burst Disk Related Hazards	✓	✓	✓		
5.9 Intermediate Pressure Relief Device Related Hazards	✓	✓	✓		
5.10 Valve Outlet Profile Specification Error in DIN 477 & EN 144	✓	✓	✓		
5.11 SCUBA Regulator Hose O-ring Retention Fault	✓	✓	✓		
5.12 First Stage Regulator O-ring Retention Design Fault	✓	✓	✓		
5.13 Hose sheath expands and bursts	✓	✓	✓		
6 Oxygen Setpoint Failures					
6.1 Oxygen Cylinder Empty		✓	✓		
6.2 Oxygen Cylinder Switched Off		✓	✓		
6.3 Oxygen First Stage Failure	✓	✓	✓		
6.4 Oxygen First Stage Over Pressure	✓	✓	✓		
6.5 Oxygen Hose Leaks	✓	✓	✓		
6.6 Oxygen Solenoid or Injector Stuck Open	✓	✓	✓		
6.7 Oxygen Solenoid or Injector Stuck Closed	✓	✓	✓		
6.8 Oxygen Manual Injector Failure Open or Closed	✓	✓	✓		
6.9 Wrong Gas in Oxygen cylinder	✓	✓	✓		

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Fault	Eliminate or Mitigate By			Annual Risk After Mitigation	
	Design	Training	Maintenance	Severity	1/Probability Risk
6.10 Oxygen fire					
6.11 Calibration using wrong gas	✓	✓	✓		
6.12 Solenoid Stuck Shut, due to rise in Intermediate Pressure	✓	✓	✓		
6.13 O2 orifice motor driver failure (orifice type injectors)	✓	✓	✓		
6.14 Use of O2 instead of Make-Up-Gas	✓	✓	✓		
6.15 Use of hypoxic Make-Up-Gas when entering water	✓	✓	✓		
6.16 Use of hypoxic Make-Up-Gas in ascent to surface		✓	✓		
6.17 Uncontrolled ascent (max 120m/min) with low PPO2	✓	✓	✓		
6.18 PPO2 low due to injection not keeping up with demand	✓		✓		
6.19 Low PPO2 set point followed by rapid ascent.	✓	✓	✓		
6.20 ALV freeflow with hypoxic Make-Up-Gas near surface	✓	✓	✓		
6.21 ALV freeflow with high PPO2 at depth	✓	✓	✓		
6.22 Left to Right Flow, instead of safer Right to Left loop flow	✓	✓	✓		
6.23 Hypoxia when OPV is on exhale counterlung during fast ascent	✓				
6.24 SCR has insufficient oxygen in gas	✓	✓	✓		
6.25 Passive oxygen addition rate incorrect (mCCRs, PA-SCR)	✓	✓	✓		
6.26 Oxygen addition button seized or stuck	✓	✓	✓		
6.27 Inaccessibility of oxygen addition button (mCCR, iCCR)	✓	✓	✓		

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Fault	Eliminate or Mitigate By			Annual Risk After Mitigation		
	Design	Training	Maintenance	Severity	1/Probability	Risk
6.28 Oxygen Sensor Temperature Compensation Error	✓	✓	✓			
6.29 PPO2 Error due to Helium Ingress to Pressure Sensor	✓	✓	✓			
6.30 Depth Exceeded for Absolute Pressure Regulators	✓	✓	✓			
7 Loop Volume Sufficiency Failures	✓	✓	✓			
7.1 Make-Up-Gas Cylinder Empty or Umbilical Supply Lost	✓	✓	✓			
7.2 Make-Up-Gas Cylinder Switched Off	✓	✓	✓			
7.3 Make-Up-Gas First Stage Failure	✓	✓	✓			
7.4 Make-Up-Gas First Stage Over Pressure	✓	✓	✓			
7.5 Make-Up-Gas Hose Leaks	✓	✓	✓			
7.6 Make-Up-Gas Manual Injector Failure	✓	✓	✓			
7.7 Wrong Gas In Make-Up-Gas Cylinder	✓	✓	✓			
7.8 Alternate Air Source Free Flow	✓	✓	✓			
7.9 No ALV or ALV Failed Off	✓	✓	✓			
7.10 Counterlungs unable to provide gas	✓	✓	✓			
7.11 BOV seal leaking, emptying loop volume	✓	✓	✓			
7.12 Flapper Valve Stuck Shut	✓	✓	✓			
7.13 Foreign Material in Breathing Hoses	✓	✓	✓			
7.14 Breathing Hoses Kinked	✓	✓	✓			
8 Loop Volume Relief Failures	✓	✓	✓			
8.1 OPV diaphragm damaged	✓	✓	✓			

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Fault	Eliminate or Mitigate By			Annual Risk After Mitigation		
	Design	Training	Maintenance	Severity	1/Probability	Risk
8.2 OPV diaphragm folded causing flood	✓	✓	✓			
8.3 Foreign material trapped under OPV diaphragm	✓	✓	✓			
8.4 Incorrect O-ring tolerance	✓	✓	✓			
8.5 OPV stuck shut	✓	✓	✓			
8.6 OPV stuck open	✓	✓	✓			
8.7 OPV cracking pressure relative to diver changes with attitude	✓	✓	✓			
8.8 OPV housing failure	✓	✓	✓			
8.9 OPV fails to shut sufficiently for positive pressure check	✓	✓	✓			
8.10 OPV interacts with water drain	✓	✓	✓			
8.11 OPV is on exhale CL instead of inhale CL where it should be	✓	✓	✓			
8.12 OPV is set incorrectly	✓	✓	✓			
8.13 OPV or drain admits water as it operates	✓	✓	✓			
8.14 Lack of means to vent loop manually when bailed out	✓	✓	✓			
9 Controller and Information Failures	✓	✓	✓			
9.1 Battery Low	✓	✓	✓			
9.2 Battery Failure	✓	✓	✓			
9.3 Power Drop-out or Battery Bounce	✓	✓	✓			
9.4 Battery life error	✓	✓	✓			
9.5 Battery overheating	✓	✓	✓			
9.6 Monitoring or control device failure not apparent to user	✓	✓	✓			
9.7 Monitoring or control device Hangs	✓	✓	✓			

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Fault	Eliminate or Mitigate By			Annual Risk After Mitigation	
	Design	Training	Maintenance	Severity	1/Probability Risk
9.8 Monitoring or control devices switched off	✓	✓	✓		
9.9 Oil Filled Chamber Leaks Oil	✓	✓	✓		
9.10 Electronic Component Explodes	✓	✓	✓		
9.11 Controller fails to handle situation where diver does not understand failure message or is unable to act	✓	✓	✓		
9.12 Faulty Software by design	✓	✓	✓		
9.13 Faulty Software by ageing	✓	✓	✓		
9.14 Monitoring or control devices Misread	✓	✓	✓		
9.15 Cracked Electronics Housing	✓	✓	✓		
9.16 Corroded wiring	✓	✓	✓		
9.17 System Looping on Interrupts, raising PPO2	✓	✓	✓		
9.18 High Voltage on Connectors	✓	✓	✓		
9.19 Brown out cycling	✓	✓	✓		
9.20 Failure to turn on	✓	✓	✓		
9.21 Single points of failure	✓	✓	✓		
9.22 EMC failure	✓	✓	✓		
9.23 Auto-Bail Out fails to operate when required	✓	✓	✓		
9.24 Auto-Bail Out operates when not required	✓	✓	✓		
9.25 Auto-On Encourages Reckless Diver Behaviour	✓	✓	✓		
9.26 Water Ingress into Electronics	✓	✓	✓		
10 Oxygen Level Monitoring Failures	✓	✓	✓		
10.1 O2 Cell Decompression Failure	✓	✓	✓		

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Fault	Eliminate or Mitigate By			Annual Risk After Mitigation		
	Design	Training	Maintenance	Severity	1/Probability	Risk
10.2 O2 Cell has CO2 Contamination	✓	✓	✓			
10.3 Load Resistor Failure in O2 Cell	✓	✓	✓			
10.4 O2 Cell Contamination	✓	✓	✓			
10.5 O2 Cell Thermal compensation failure	✓	✓	✓			
10.6 O2 Cell Loose Connection	✓	✓	✓			
10.7 O2 Single Cell Failure	✓	✓	✓			
10.8 O2 Cell Failures Tracked Incorrectly	✓	✓	✓			
10.9 O2 Two Cell Failure	✓	✓	✓			
10.10 Majority of O2 cells fail during dive	✓	✓	✓			
10.11 O2 Cell Calibration Incorrect	✓	✓	✓			
10.12 O2 Cells show different reading to independent PPO2 monitor	✓	✓	✓			
10.13 O2 Cells have condensation or vapour on sensor face	✓	✓	✓			
10.14 O2 Cells have differential pressure applied	✓	✓	✓			
10.15 O2 Cell Explodes or Leaks	✓	✓	✓			
10.16 Oscillating sensor	✓	✓	✓			
10.17 Caustic Burn from leaking electrolyte	✓	✓	✓			
10.18 Diver fails to monitor PPO2	✓	✓	✓			
10.19 Oxygen cells sensitive to CO2	✓	✓	✓			
11 Carbon Dioxide Level Failures	✓	✓	✓			
11.1 Scrubber Not Fitted	✓	✓	✓			

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Fault	Eliminate or Mitigate By			Annual Risk After Mitigation	
	Design	Training	Maintenance	Severity	1/Probability Risk
11.2 Scrubber Physically Damaged, affecting gas X-section	✓	✓	✓		
11.3 Scrubber Exhausted	✓	✓	✓		
11.4 Scrubber Bypass	✓	✓	✓		
11.5 Excess Work of Breathing	✓	✓	✓		
11.6 Counterlungs change position, causing CO2 hit	✓	✓	✓		
11.7 One Way Valve (Flapper valve) Stuck Open or Partially Open	✓	✓	✓		
11.8 One Way Valve (Flapper valve) Stuck Shut or Partially Shut	✓	✓	✓		
11.9 One Way Valves missing on one side	✓	✓	✓		
11.10 Caustic cocktail from CO2 scrubber	✓	✓	✓		
11.11 Hoses pinched or kinked	✓	✓	✓		
11.12 Loop Flow Direction Swapped Accidentally	✓	✓	✓		
11.13 Premature Counterlung Failure	✓	✓	✓		
11.14 Counterlung blocks ports	✓	✓	✓		
11.15 Structures that bypass the scrubber	✓	✓	✓		
11.16 Very low diver tidal volume	✓	✓	✓		
11.17 Sensory system false alarm	✓	✓	✓		
12 Flooding and Drowning	✓	✓	✓		
12.1 Loop Flood	✓	✓	✓		
12.2 Mouthpiece floods rebreather	✓	✓	✓		
12.3 Mouthpiece failure (i.e. failure to allow diver to breathe from loop when this is desirable)	✓	✓	✓		

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Fault	Eliminate or Mitigate By			Annual Risk After Mitigation	
	Design	Training	Maintenance	Severity	1/Probability Risk
12.4 Counterlung ports pull out from counterlung	✓	✓	✓		
12.5 Implosion or explosion on compression or decompression	✓	✓	✓		
12.6 Counterlung or hose pinched	✓	✓	✓		
12.7 Counterlung or rebreather component pierced	✓	✓	✓		
12.8 Lack of water drain	✓	✓	✓		
12.9 Water Drain Failure	✓	✓	✓		
13 Other Rebreather Equipment Failures	✓	✓	✓		
13.1 Pressure causing implosion	✓	✓	✓		
13.2 Rebreather BC Failure	✓	✓	✓		
13.3 Harness Failure	✓	✓	✓		
13.4 Pressure Sensor Failure.	✓	✓	✓		
13.5 Noxious chemical off-gassing	✓	✓	✓		
13.6 Entrapment Hazard	✓	✓	✓		
13.7 BOV or DSV Guillotines Diver's Tongue	✓	✓	✓		
13.8 Infective Bacteria, Fungi, Yeasts and Viruses	✓	✓	✓		
13.9 Insects inside loop	✓	✓	✓		
13.10 Argon Narcosis from using less than 99% pure Oxygen	✓	✓	✓		
14 Associated Equipment Failures	✓	✓	✓		
14.1 Gross dry suit leak	✓	✓	✓		
14.2 Entrapment Hazard	✓	✓	✓		
14.2 Polarised Mask Hazard		✓			
15 Decompression Computer Failures	✓	✓	✓		
16 Failures Specific to Dives in Cold Water	✓	✓	✓		

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Fault	Eliminate or Mitigate By			Annual Risk After Mitigation	
	Design	Training	Maintenance	Severity	1/Probability Risk
16.1 Effect of cold on the rebreather	✓	✓	✓		
16.2 Thermal respiratory shock	✓	✓	✓		
17 Failures Specific To Umbilical-Supplied Dives	✓	✓	✓		
17.1 Loss of Umbilical (Commercial diver)	✓	✓	✓		
17.2 Cut of umbilical near surface (Commercial Diver)	✓	✓	✓		
17.3 Entrapment of Umbilical (Commercial diver)	✓	✓	✓		
17.4 Loss of Helmet (Commercial diver)	✓	✓	✓		
17.5 Sudden change in depth (Commercial diver)	✓	✓	✓		
17.6 CO in loop (Commercial diver)	✓	✓	✓		
17.7 HC or Volatile Organic Compounds in Loop (Commercial diver)	✓	✓	✓		
17.8 Loss of communications (Commercial Diver)	✓	✓	✓		
17.9 Loss of Gas Heating (Commercial diver)	✓	✓	✓		
17.10 Overheating (Commercial diver)	✓	✓	✓		
17.11 Loss of Suit Heating (Commercial diver)	✓	✓	✓		
17.12 Excess suit heating (Commercial diver)	✓	✓	✓		
17.13 Tools and Equipment (Commercial diver)	✓	✓	✓		
17.14 Oro-nasal one-way valve failure (Commercial diver)	✓	✓	✓		

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Fault	Eliminate or Mitigate By			Annual Risk After Mitigation		
	Design	Training	Maintenance	Severity	1/Probability	Risk
17.15 Gas manifold one-way valve failure (Commercial diver)	✓	✓	✓			
17.16 Loss of Umbilical Gas	✓	✓	✓			
17.17 Bail-Out Gases Used instead of Oxygen	✓	✓	✓			
18 Diver Physiology Related Faults	✓	✓	✓			
18.1 Hypoxia	✓	✓	✓			
18.2 Hyperoxia	✓	✓	✓			
18.3 Hypercapnia	✓	✓	✓			
18.4 Breathing off loop that otherwise cannot sustain life	✓	✓	✓			
18.5 Allergic Reaction to Material	✓	✓	✓			
18.6 Vomiting into breathing loop	✓	✓	✓			
18.7 Deco dive with incorrect PPO2 level in loop	✓	✓	✓			
18.8 DCS risk higher than statistical projection of deco algorithm	✓	✓	✓			
18.9 Respiratory collapse from WOB	✓	✓	✓			
18.10 Respiratory collapse from thermal respiratory shock	✓	✓	✓			
18.11 Respiratory collapse from asthma	✓	✓	✓			
18.12 Respiratory collapse from water inhalation	✓	✓	✓			
18.13 Respiratory collapse from pressure surge	✓	✓	✓			
18.14 Respiratory Collapse (General)	✓	✓	✓			
18.15 CNS Toxicity	✓	✓	✓			
18.16 Pulmonary O2 Toxicity	✓	✓	✓			
18.17 Counter-diffusion hazard	✓	✓	✓			

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Fault	Eliminate or Mitigate By			Annual Risk After Mitigation	
	Design	Training	Maintenance	Severity	1/Probability Risk
18.18 Sudden Underwater Blackout	✓	✓	✓		
18.19 Immersion Pulmonary Oedema (IPO)	✓	✓	✓		
19 General Diving Hazards (Technical Diving)	✓	✓	✓		1000
20 Safety Process Failures	✓	✓	✓		
20.1 FMECA Incompleteness	✓	✓	✓		
20.2 Incompetent or negligent developer	✓	✓	✓		
20.3 Incompetent or falsified certification		✓	✓		

22 REFERENCES:

1. D.H. Elliott & R.E. Moon, "Long Term Health Effects of Diving", Ch21, pp585-604 of The Physiology and Medicine of Diving, P. Bennett & D. Elliott, 4th Edition.
2. D.H. Elliott & P.B. Bennett, "Underwater Accidents", Ch9, pp238-252 of The Physiology and Medicine of Diving, P. Bennett & D. Elliott, 4th Edition.
3. DAN (Divers Alert Network) Reports available from http://www.diversalertnetwork.org/
4. British Sub Aqua Club Accident Reports, from http://www.bsac.org/safety/index.html
5. International Marine Contractors Association reports, from http://www.imca-int.com/divisions/marine/publications/dpsi.html
6. UK Health and Safety Laboratory Research Report 424, "Performance of Diving Equipment" by N. Bailey, J. Bolsover, C Parker and A Hughes, 2006
7. A. Deas, "How Rebreathers Kill People", available from http://www.deeplife.co.uk
8. Stephen Hawkings, "Diver Mole Web Site", at http://www.btinternet.com/~madmole/divemole.htm and available long term through www.archive.org.
9. S. Tetlow, J. Jenkins, "The use of fault tree analysis to visualise the importance of human factors for safe diving with closed-circuit rebreathers (CCR)", *International Journal of the Society for Underwater Technology, Vol 26, No 3, pp 51-59, 2005, ISSN 0141 0814.*
10. Air Products, A review of air separation technologies. Available for download from http://www.airproducts.com/~/media/downloads/white-papers/A/en-a-review-of-air-separation-technologies-whitepaper.pdf Capture date of 12th June 2013

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11. NASA data on "Outgassing Data for Selecting Spacecraft Materials" http://outgassing.nsa.gov, Capture date of 3rd September 2008
12. Boedeker Plastics, Outgasing of Engineering Plastics in High-Vacuum Applications, www.boedeker.com/outgas.htm, Capture date of 4th April 2012
13. Polymer Data Handbook 1999, Edited by James Mark (109 Authors), Published Oxford University Press. Available from www.oup-usa.org with a Capture date of 15th March 2007.

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